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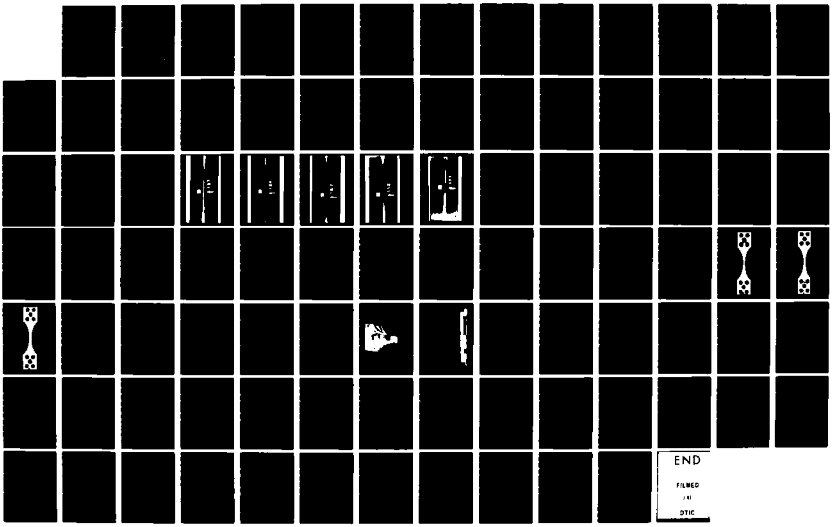

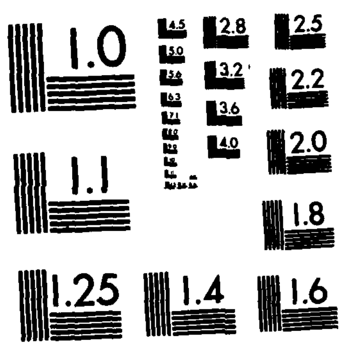

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ULTRASONIC INSPECTION AND FATIGUE EVALUATION OF CRITICAL PORE SIZE IN WELDS

SEPTEMBER 1981

CLARENCE J. CARTER
JOHN J. CONNELLY
RAYMOND A. CELLITTI

INTERNATIONAL HARVESTER COMPANY
SCIENCE AND TECHNOLOGY LABORATORY
HINSDALE, ILLINOIS 60521

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Controlled amounts of weld porosity were introduced into double-vee butt weld joints of low-alloy, high strength structural steel using a gas metal arc weld method. The weld zones were inspected radiographically and ultrasonically to detect and classify porosity severity. Subsequent uniaxial fatigue tests indicated that mean fatigue life of "water clear" weld was superior to the mean fatigue life of weldments of all pore sizes.

Fracture toughness (KIC) as measured by Charpy impact under dynamic loading was noted to improve with weld specimens containing fine pores (0.024 inch diameter and under).

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FORWARD

This final technical report under Contract No. DAAG46-76-C-0058 entitled, "Ultrasonic Inspection and Fatigue Evaluation of Critical Pore Size in Welds" covers the period August 16, 1976 to November 30, 1979.

This project has been accomplished as part of the U.S. Army Materials Testing Technology Program, Project No. M-766-350 which has for its objective the timely establishment of testing techniques, procedures or prototype equipment to ensure efficient inspection methods for materiel/material being procured or maintained by the Army.

This contract with International Harvester Company, Science and Technology Laboratory, Hinsdale, Illinois was administered by Army Materials and Mechanics Research Center under the technical direction of Mr. R. H. Brockelman (AMMRC).

Project activities were coordinated under the technical guidance of Mr. R. A. Cellitti, Manager Metallurgical Processes Research. Other areas of technical responsibility were provided by Mr. C. J. Carter, Development Engineer and Mr. J. J. Connelly, Sr. Development Engineer. The authors gratefully acknowledge the technical assistance of other IH team members who contributed substantial efforts.

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INTRODUCTION

For design purposes and to obtain adequate service performance of welded structures, a study was made to quantify the extent that weldment flaws affect operational service life. Although the presence of cracks, lack of fusion, and elongated inclusions exert a more damaging condition in high strength steel, this initial study was primarily concerned with various levels of controlled porosity in steel plates (50,000 psi yield strength) with a double-vee butt-weld joint.

Five porosity levels were produced that parallelled ASME boiler and pressure vessel code specification (Section VIII). Appendix IV of the pressure vessel code details acceptance standards for radiographically determined porosity in welds. Permissible size and number of pores are specified for 4 levels (assorted, large, medium and fine). This program included "water clear" as the fifth level.

The primary objectives of the program were:

1. Establish various process (gas metal arc welding) parameters for producing controlled porosity and prepare butt-weld plates for 5 porosity levels.

2. Establish optimum procedure for ultrasonic inspection and classification of various porosity levels.

3. Ultrasonically evaluate weld plates and the uniaxial fatigue specimens prepared from weld plates representative of various porosity levels.

4. Ascertain relationship between fatigue life and porosity level.

The material primarily investigated was low alloy, high strength steel designated as IH-50X with a minimum yield strength of 50,000 psi. Additionally, armor steel plate (MIL-S-12560B) was welded and tested.

2. MATERIALS

2.1 Chemistry

The IH-50X material was procured in the form of 3/4 inch thick plates.

The nominal steel chemistry is shown below.

C	Mn	Si	Cu	Cb
0.22	1.10	0.10	0.20	0.01

Armor Steel of MIL-S-12560B specification was procured in the form of 1 inch thick plate. The steel chemistry is shown below.

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Al
0.25	0.25	0.010	0.020	0.20	0.07	3.09	1.00	0.35	0.021

2.2 Material Preparation

Sample test plate sections of 1 inch x 24 inches were cut from procured plates (76 inches x 152 inches) as initial preparation in producing weld plates of 14 inches x 24 inches. The section plates were cut to obtain a finished fatigue specimen with a longitudinal direction. All sectioned plates were bevelled at one end by flame cutting. The bevelled ends and adjacent flat surfaces were subsequently cleaned by shot blasting.

Figure 1 illustrates the double-vee butt joint which was produced and utilized throughout the study.

2.3 Base Material Properties

Duplicate tensile specimen blanks were sectioned from the IH-50X plate (3/4") and armor steel plate (1"). Tension tests conducted on 0.505 inch dia. specimens are shown below.

Ident.	UTS, psi	YS, psi (.2% offset)	% R.A.	% Elong.
IH-50X	70,500	50,600	23.0	59.0
IH-50X	72,900	49,900	22.0	56.8
Armor Stl.	169,500	155,000	48.1	13.5
Armor Stl.	168,900	155,100	47.0	13.5

Note: IH-42X was initially planned for preparation and evaluation of weld porosity. However, tested yield strength was 37,000 psi and did not meet the minimum yield strength requirement of 42,000 psi. Accordingly, the higher strength IH-50X was utilized.

3. CONTROLLED POROSITY STUDY

The intent of this study was to develop a suitable method for producing porosity and preparing weld specimens (fatigue and fracture toughness) with controlled levels of porosity. Figure 2 shows porosity charts (ASME Boiler and Pressure Vessel Code) which classify and designate the number and size of pores in any six inch length of weld of 3/4 inch thickness. Several weld parameters were varied to obtain the pore size and content for various porosity levels sought. All weld plates were prepared using the gas metal arc welding process.

The electrode wire was type E70S-3 of the following analysis.

Carbon	.06 to .15
Manganese	.90 to 1.90
Silicon	.45 to .70
Phosphorus	.025
Sulfur	.035

Systematically adjusted process variables included (1) wire feed (2) travel speed and (3) shielding gas mixture and flow rate. Four weld passes were made along the 24 inch length (cross-section is shown in Figure 1). A shielding gas of argon +2% oxygen was used initially for all four passes. Other variables were as follows:

Gas flow rate	-	35 ft^3/hr.
Wire feet rate	-	360 inches/min.
Travel speed	-	15 inches/min.
Voltage	-	30 v

Large pores were produced using this technique. However, radiographic inspection of the initial plates indicated a lack of fusion. Lack of fusion was remedied by using argon +25% carbon dioxide shielding gas for all root passes. Argon +2% oxygen was used for producing the various levels of porosity in the surrounding top passes of the weld layers.

Table I lists some of the plates with the welding parameters varied to produce the levels of porosity sought. Note, "water clear" welds were produced with the use of argon +25% CO_2 shield gas for root and top weld layers. Radiographic inspection of weld plates were continuously made to measure the influence and adjustment requirements for weld parameters. Approximately 70 weld plates of IH-50X and 20 weld plates of armor plates with the various levels of porosity were produced in this manner.

4. INSPECTION PROCEDURES

4.1 Radiographic Inspection

The weld zone of each ground plate for weld crown removal was inspected by radiography (MIL Std. 453). Radiographic inspection controls are indicated below.

Source to film distance	44 inches
Qulality level	2-2T
Film type	Dupont NDT 55
Exposure	260 KV, 12 MA, 1 min.
Focal spot	4 mm
Film screen	.005 inch (front) .010 inch (back)

Representative radiographs showing the 5 porosity levels are presented as Figures 3 through 7.

4.2 Ultrasonic Inspection

An ultrasonic calibration standard containing various size diameter flat bottom holes (1/16, 1/8, 3/16 and 1/4 inch diameters) was prepared from a 3/4 inch plate of IH-50X. Plate dimensions and locations of the holes are shown in Figure 8.

The IH automatic-computerized ultrasonic inspection system was used to measure pore size (area). A block diagram of the system is shown in Figure 9.

The amplitude of a signal displayed on the cathode ray tube corresponds to a certain D.C. analog voltage. This voltage is continuously sampled (every 1/750 sec.) by an analog to digital converter and stored in computer memory for subsequent retrieval and mathematical processing. The ultrasonic signals are electronically monitored and classified. The signal amplitude or D.C. voltage is divided into 16 category levels (Category 1 to Category 16). Category 1 represents small pores and Category 16 represents large pores.

Category	D.C. Volts Range Corresponding to Category (Negative Values
1	0 to 0.62
2	0.63 to 1.25
3	1.26 to 1.87
4	1.88 to 2.50
5	2.51 to 3.12
6	3.13 to 3.75
7	3.76 to 4.37
8	4.38 to 5.00
9	5.01 to 5.62
10	5.63 to 6.25
11	6.26 to 6.87
12	6.88 to 7.50
13	7.51 to 8.12
14	8.13 to 8.75
15	8.76 to 9.37
16	9.38 to 10.00

As the transducer scans (longitudinally) the weld zone, a continuous count of various size pores are stored in computer memory. At the termination of the scan or multiple scans, the computer is automatically instructed (via Electronic occupancy switch) to perform a mathematical operation which results in a quantitative soundness rating. By way of example, the following operation is automatically performed as follows:

Soundness index rating = $F_1 \times P_1 + F_2 \times P_2 + F_i \times P_i$
where:

Fi = Percent of counts occurring for Category i

Pi = Weighting factor for Category i

The format generated by the computer via teletype printer is illustrated in Figure 10.

From let to right, the first column lists the categories 1 through 16. The second column details the number of counts that occurred for individual categories or pore sizes. The third column (percent count) is the ratio of counts for Category 1 to the total number of counts. The fourth column shows the progression factors selected for each category and the last column (product) is obtained by multiplying the values of column three and four of the same category number. The soundness index is the sum of the individual product values that appear in the fifth column. The progression factors were obtained by the following exponential formula; $1.62^{(n-2)}$ where n corresponds to category number.

4.2.1 Inspection Apparatus

Basic inspection facilities for immersion testing consisted of a water tank of dimensions 2½ ft. deep x 3 ft. wide x 10 ft. long with a motorized scanning bridge to which the transducer was attached. The active element of the transducer is composed of lithium sulfate (3/4 inch in diameter) with a 7 inch focal length in water and an operating frequency of 5 MHz. A lithium sulfate transducer was selected due to its exceptional performance as a receiver of ultrasonic energy.

4.2.2 Ultrasonic Inspection

Inspection of full size (14" x 24") welded plates were conducted using an angle (45^{o}) beam scan and longitudinal scan. The angle beam scan was parallel to the 24" length zone.

Inspection of the weld zone width was made by lateral indexing the transducer in 0.050 inch increments at the ends of each longitudinal scan. That is, 15 longitudinal scans were made to cover a 3/4 inch width weld zone (0.050 x 15 = .75).

The ultrasonic instrumentation was calibrated by angle alignment of the transducer with a 1/16" dia. flat bottom hole machined in a 3/4 inch thick plate. The ultrasonic sensitivity control was adjusted to equate the signal response (voltage level) from the reference hole (1/16" dia.) with category level 16 (9.375 v to 10.0 v range). Successively smaller categories (15, 14---0) represent lower voltages, and smaller size defects. The voltage range for each category level is 0.625 volts. (An increase in counts of Category 16 over an equivalent number of counts which occur in Category 15 indicate that defects larger than the reference indication, 1/16" dia. hole are present).

Ultrasonic printout data of several representative plates using a longitudinal scan are shown as Figures 10 through 15. Ultrasonic printout data sheets of several plates which were inspected by immersed angle beam are shown in Figures 16 through 23. Note the difference in inspection response with Plate #162 (Figures 13 and 21) using an angle beam technique. The cleanliness rating indices for most of the plates inspected are listed in Table II.

5. SPECIMEN LOCATION AND PREPARATION

To test the effect of various porosity levels, a uniaxial loaded fatigue specimen was designed to provide the largest cross-sectional test area. Figure 24 shows the specimen configuration. Specimen blanks (3/4" x 3" x 14"), which were initially referenced to radiographic porosity levels, were sectioned from the weld plates. Weld zones of the several blanks were inspected using various ultrasonic techniques to determine optimum response for different search unit orientations. Specimen blanks sectioned from plates No. 116 and 180, which contained an assorted size of pores, were inspected by longitudinal immersion and contact methods as well as angle beam (45°) immersion and contact methods.

To obtain a more precise measure of large size pores, the ultrasonic instrumentation was recalibrated with a 1/8" diameter flat bottom hole. A 2 inch video amplitude which corresponded to -9.8 volts resulted in an instrument gain setting of 14.0 db. Table III shows the corresponding voltage levels and gain settings (db) for several large size pores (approx. 1/8 inch diameter) using longitudinal immersion and angle beam contact search units. The gain setting for angle beam measurement (area) of the pore size required decreasing the gain to correspond to an inch video amplitude signal from the 1/8 inch dia. (25 db and 4.9 volts) flat bottom hole. By manual relocation of search unit and varying angle beam orientation with the individual pores, a more sensitive response was obtained. The sensitivity from pore No. 1 (plate 116) was increased 36% (6.67 volts versus 4.9 volts). Higher defect response was obtained by contact angle beam inspection with subsequent orientation measurements made and shown in Table IV. Initial measurements were with the angle beam oriented $90^{\circ}$to the weld pass or line.

Pore No. 4 was also ultrasonically measured from the opposite plate face at various orientation angles to the weld line. The results were as follows:

Search Unit Orientation	Reflected Voltage from Pore
Perpendicular to weld line	7.49 volts
35^{o} right of perpendicular	11.25 volts
20^{o} left of perpendicular	10.13 volts

These results emphasize the importance of adjusting (rotating) search unit orientation to obtain maximum ultrasonic response from irregular shaped pores. The remaining specimen blanks were inspected to determine porosity magnitude and position of various size pores in the specimen test zone. All measurements were made with a contact angle beam (45^{o}) search unit.

5.1 Specimen Fixturing

Specimen fixtures were designed and machined to test flat unaxial fatigue specimens under tension-tension loading. Universal joints were incorporated at both loading ends to assure axial alignment during loading. Strain gages were mounted on opposite flats of initial specimen test section and monitored. Stress deviations as indicated by the strain gages were less than 0.4% at maximum stress (53,000 psi). However, initial specimens were prepared with a 2½ inch width grip section which resulted in premature fracture at bolt holes in the grip section. Additional strain gages were mounted on the grip section sides opposite the bolt holes. A static load equivalent to 4% above the proportional limit was applied. The strain gages indicated that yielding was occurring on grip edges adjacent to clamping holes.

The grip width of prepared specimens was suitably increased by welding ½ inch flats to the edges and flush grinding the flats. Subsequent specimens were prepared with a wider grip section.

6.0 MECHANICAL TESTS

6.1 Uniaxial Fatigue

After a satisfactory specimen design was obtained, base line specimens of IH-50X were tested in tension-tension loading at a stress ratio (min./max.) of 0.1.

Maximum test stress was 55,000 psi (30,000 lbs.). Base material results are shown in Table V. Figure 25 shows a Weibull plot of the data points. Pertinent Weibull parameters calculated from the data points are listed below:

Slope	=	3.38
Mean life	=	448,984 cycles
Characteristic life	=	500,342 cycles
Standard deviation	=	147,339 cycles
Median life	=	448,948 cycles

The 95% confidence limit for each sample is also plotted as a vertical rectangle. It is interesting to note that the median and mean life coincide and the curve approximates a normal distribution with a slope of 3.5.

Fatigue specimens representing the various porosity levels were then tested at the same maximum stress level and cyclic stress ratio (0.1). Prior to testing, all specimens were radiographed. Figures 26 through 28 are radiographs of several representative porosity levels. Table VI shows the ultrasonic signature number for each specimen tested along with uniaxial fatigue test results. The identification of weld plates from which specimens were sectioned are also shown.

Weibull plots of the data (cycles to failure) for each porosity level based on ultrasonic results (Table X) are shown in Figures 29 through 33. The pertinent Weibull parameters are shown for each porosity level in Table VII. Photomacrographs showing the fracture surfaces of select weld specimens are shown in Figures 34 and 35.

6.1.1 Armor Plate Specimens

Initially, several specimens were loaded monotonically (prestrained 0.1%) to determine maximum load requirement.

Maximum capacity of the fatigue machine load frame is 100,000 psi under monotonic loading and 75,000 psi under cycle loading. The initial specimen was loaded to 76,300 lbs. (143,000 psi) to determine an offset strain of 0.1%.

Base specimens of armor plate material were initially tested at a maximum stress level of 100,000 psi. Failure occurred at an early cycle life and maximum stress level was reduced to 80,000 psi. Table VIII shows fatigue test data for base line and weld specimens.

After testing Sample 4A (base material with two million cycles), the balance of the specimens were tempered at 1300F to lower material strength to approximate the strength of IH-50X steel. The lowest hardness obtainable after temper was Rc 25.

A log stress versus log cycle plot of armor steel specimen data is presented as Figure 36. The inverse slope of the regression line was calculated to be 33.3 with an intercept at 1 cycle of 113,000 psi. Other regression parameters were as follows:

Mean life	=	237,000 cycles
Mean stress	=	83,000 psi
Std. deviation	=	7,800 psi

6.2 Fracture Toughness

The ASTM (E-399) minimum recommended thickness and crack length for adequate specimen size should be greater than 2.5 $(Kic/\sigma_y)^2$. The ratio of σ_y/E in ASTM-E399 also gives a guide for selecting adequate specimen thickness. The yield strength of the material (IH-50X) is 50,000 psi. The corresponding ratio of σ_y/E is 0.00167 which would require a specimen in excess of 3 inch thickness.

Therefore, it was considered appropriate to utilize a v-notch square (0.394 inch) Charpy specimen in which a correlation between fracture toughness (Kic) and Charpy impact energy has been established by J. M. Barsom and S. T. Rolfe.[3]

The correlation equation is of the form

$$(Kic/\sigma_y)^2 = \frac{5}{\sigma_y} \; (CVN - \sigma_y/20)$$

Where:

Kic = Plain strain fracture toughness

σ_y = .2% offset yield strength

CVN = Charpy impact energy

Square v-notch Charpy specimens were machined from IH-50X weld plates representing various porosity levels and impact tested at 80°F. The test data is shown in Table IX along with calculated fracture toughness values.

Visual observation of fracture specimens indicated that pores were occasionally situated at or just below the notch root surface. This situation was prevalent with Specimen #9 which contained a large pore at the notch root. Specimens containing fine scattered porosity exhibited the highest impact strength and fracture toughness. This is believed to result from a beneficial crack arrest structure. That is, a propagating crack will require a higher crack reinitiation energy level at a pore site. In the absence of a pore, a lower energy level is adequate to sustain crack propagation.

7.0 ANALYSES & DISCUSSION

Table VI shows the grouping of various porosity levels based on radiographic results. Table X shows a regrouping of specimen porosity levels based on ultrasonic (category) results. Regrouping was in accord with the following criteria:

Porosity Level	Ultrasonic Category Range
Clear	1 to 1.5
Fine	1.6 to 3.2
Medium	3.3 to 7.1
Assorted	7.3 to 11.2
Large	11.3 to 16

A comparison of fatigue response (mean life cycles) for the various porosity levels by Weibull method gave the following mean life ratio in comparison with the base material. (Mean life of porosity material ÷ mean life of base material.) Mean life (base material) = 449,000 cycles.

The mean life of each porosity level along with other Weibull parameters are presented in Table XI.

Mean Life Ratios

	Clear	Fine	Medium	Large	Assorted
Radiographic	.50	.36	.40	.53	.65
Ultrasonic	.56	.46	.42	.52	.24

There is no appreciable (approx. 6%) change in the mean life ratios between a clear weld and weld zone with a large pore. (.125 inch dia.) This large pore size represents an area of .01213 in^2 contained in a cross-sectional specimen area of .4906 in^2 which represents 2.5% of the area. There is a lower mean life with fine and medium size pores (approx. 20%). Apparently, the pore size of 1/8 inch diameter associated with Category 16 does not affect uniaxial fatigue strength. These results are in agreement with published data by C. F. Boulton, "Acceptance Levels of Weld Defects for Fatigue Service."[4]

Mr. Boulton's fatigue results showed that severe porosity (3% by volume) was commensurate with low porosity(1% of projected area per inch of weld thickness). That is, fatigue response for severe and low porosity levels were comparable. A plot (C. F. Boulton) showing results for severe and low porosity fatigue specimens is presented as Figure 37.

A difference in fracture toughness response between porosity levels was noted with v-notch square Charpy specimens. Fine porosity (0.024 inch diameter max.) which exhibited the highest fracture toughness values is due to a superior crack arrest texture.

The mean value difference in fracture toughness response for fine pores (157 Ksi-in$^{\frac{1}{2}}$) and large pores (124 Ksi-in$^{\frac{1}{2}}$) is 27%. In addition to improved crack arrest texture, the occurrence of fine pores at the notch root are less severe than large pores in crack initiation. An increased scatter of toughness response was noted with large size pores. This is thought to be caused by a more variable area of the large pores occurring at the notch root and along the fracture path. The weld pores were ultrasonically located and positioned (during specimen machining) to coincide as close as possible with the fracture plane through the notch root.

Although the instrumentation was calibrated with a 1/8 inch diameter standard, larger pores of approximately 3/16" diameter were located and positioned in several specimens.

One 3/16 inch diameter pore represents 5% of fatigue specimen cross-sectional weld area. A 3/16 inch diameter pore also represents 22% of the Charpy specimen cross-sectional weld area.

8.0 SUMMARY OF RESULTS

Various levels of controlled porosity were produced in butt welded 3/4 inch thick steel plate by gas metal arc welding. Lack of fusion was eliminated by using argon - 25% carbon dioxide shielding gas for root passes. Pore sizes and numbers were determined by radiographic and ultrasonic test methods. A second order equation was found to relate ultrasonic signature number of pore size with radiographic pore size classification. The equation is $y = .23x^2 + 1.74\,x - 0.17$. Where x is an integer from 1 to 5 representing radiographic pore classification (1-clear, 2-fine, 3-medium, 4-mixed, 5-large) and y is the corresponding ultrasonic pore classification. Uniaxial fatigue tests of specimens containing specific pore classification indicated that the mean fatigue life of "water clear" welds were superior to the mean fatigue life of all pore containing welds at maximum test stress level of material yield strength (55,000 psi).

Difference in mean fatigue life for various pore sizes (ultrasonically measured) compared to "water clear" weld:

Pore Size	% Reduction or Gain in Mean Fatigue Life
Fine	-16
Medium	-24
Large	- 6

A more accurate detection and classification of large pore sizes was obtained by manual varying search unit (contact) orientation with respect to pore location. This is believed to be due to variable scatter of ultrasonic radiated energy upon impingement with irregular shaped pores. Fracture toughness measurements made with Charpy v-notch specimens indicated that fine pores improved toughness approximately 5% in comparison with "water clear" weld toughness.

Difference in average fracture toughness (K_{IC}) for various pore sizes compared to "water clear" weld:

Pore Size	% Reduction or Gain in Average Fracture Toughness
Fine	+ 5
Medium	- 1
Large	-17

9.0 CONCLUSIONS

1. Controlled porosity was produced in butt weld joints of 3/4 inch thick steel plates by selective adjustments of shield gas composition, gas flow rate, electrode wire feed and voltage.
2. The optimum ultrasonic inspection method for detecting pores was noted to be an angle beam technique in which the search unit orientation to the weld seam is varied similar to a saw tooth or zig-zag scan. That is, pore sites should be approached from several directions due to nonuniform scatter of ultrasonic energy in different directions.
3. The relation between ultrasonic signature number and pore size was calculated from a graphical plot and noted to be of the following form.

$$y = 0.23\,x^2 + 1.74\,x - 0.17$$

where

y = Ultrasonic signature number

x = Pore diameter size (inches)

4. No appreciable impairment of fatigue life in 55,000 psi steel was noted with porosity levels which were 50% above the maximum allowable dimension (0.125 inch) for 3/4 inch thick plate. The mean life ratios of fine and medium size pores showed a reduction of approximately 20% in comparison to "water clear" mean life ratio (mean life of weld ÷ mean life of base plate).

   More crack initiation sites are present in the specimen test zone with fine pores. Additionally, there is more material around the sites of the smaller pores. After initiation of cracks at these high stress concentration sites, rapid crack growth occurs by connection and extension across multiple pore sites. With larger size pores, pore frequency or occurrence is less and fewer crack growth paths between pores are lengthened considerably.

5. Fracture toughness as measured by v-notch square Charpy specimens was noted to improve with fine (0.024 inch or less) porosity levels over "water clear" weld and is attributed to an improved crack arrest texture. Conversely, fracture toughness decreased with large size pores. Pore size magnitude shows an opposite effect on fracture toughness properties as compared with uniaxial fatigue. The crack is initiated by a sharp V-notch which has a smaller radius than the fine pore size. A fine pore causes the crack to arrest and reinitiate at a higher energy level than required to sustain normal crack growth.

   As the pore size increases, fewer pore sites are available to arrest a running crack and the cross-sectional area along the fracture plane is considerably reduced (22%) by a large pore.

6. Weld specimen response containing various size weldment pores is dependent upon the material property under evaluation. The effect of weld pore size on fracture toughness is opposite to the pore size effect on uniaxial fatigue.

10.0 RECOMMENDATIONS

1. A review of the various weld standards should be made to ascertain if the limiting pore level acceptance is adequate for the principal material properties and loading conditions the weldment will experience under service conditions.
2. Additional studies are recommended to quantify the extent various severities (% pores by volume) of equal pore size levels influence fatigue life of weldments.
3. Additional studies are needed to quantify the extent the impairment in fracture toughness as a function of weld porosity severity (% pores by volume) for various pore sizes.
4. Ultrasonic inspection with an angle beam technique is recommended as the most suitable means for detection of pores.
5. The recommended instrumentation and procedure for inspection of butt welds are detailed in the Appendix.

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1. "Standard Recommended Paractice for Detection of Large Inclusions in Bearing Quality Steel by the Ultrasound Method," Method B, ANSI/ASTM E588-76.

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3. J. M. Barsom and S. T. Rolfe, "Correlation Between Kic and Charpy V-Notch Test Results in the Transition Temperature Range," Impact testing of Metals, ASTM - Special Technical Publication 466, 1970, pp. 281-302.

4. C. F. Boulton, "Acceptance Levels of Weld Defects for Fatigue Service," paper presented at Annual Welding Society Meeting, May 4, 1976 in St. Louis, Missouri.

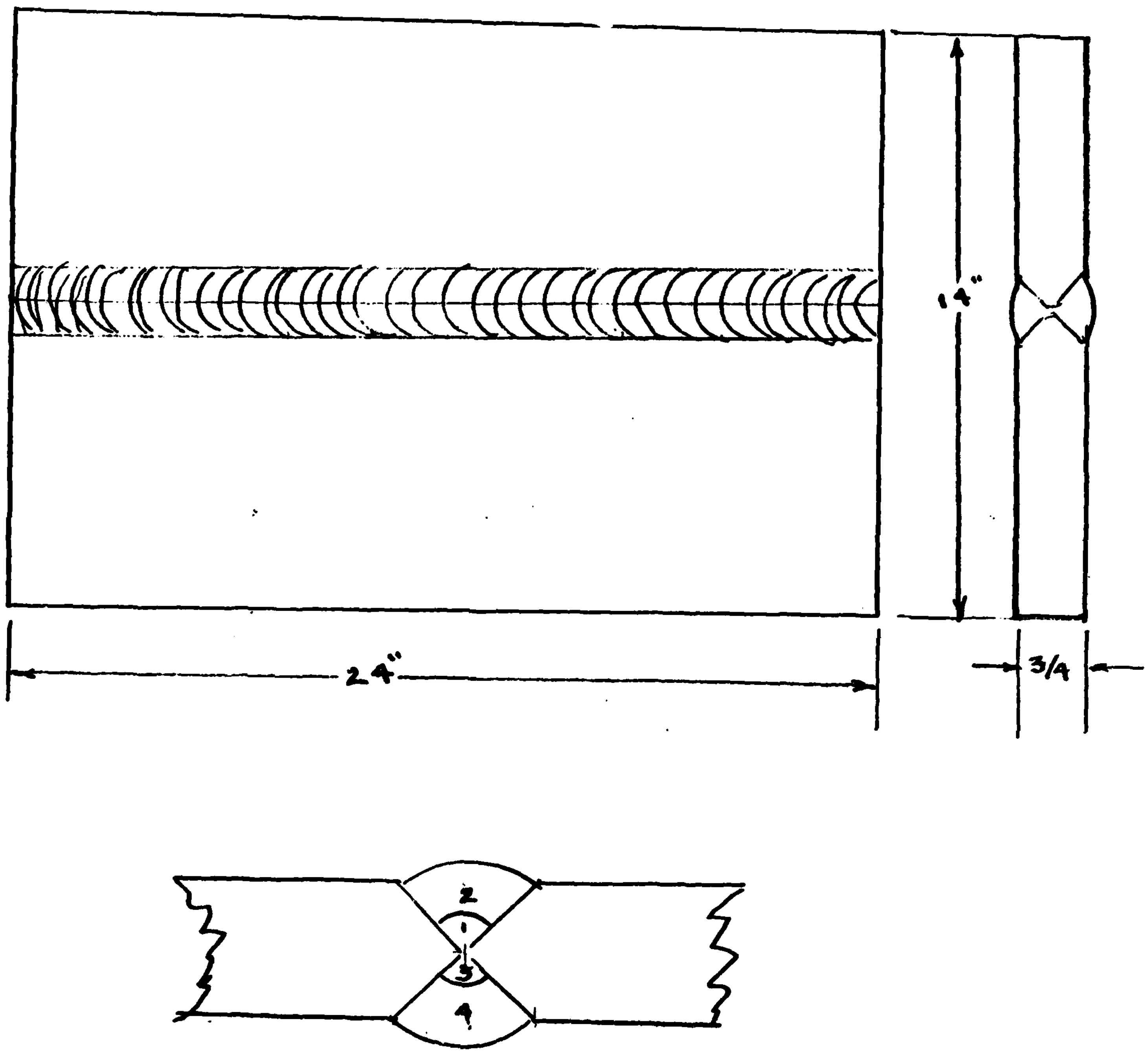


FIGURE 1 DOUBLE-VEE BUTT JOINT OF 3/4 INCH THICK WELD PLATES

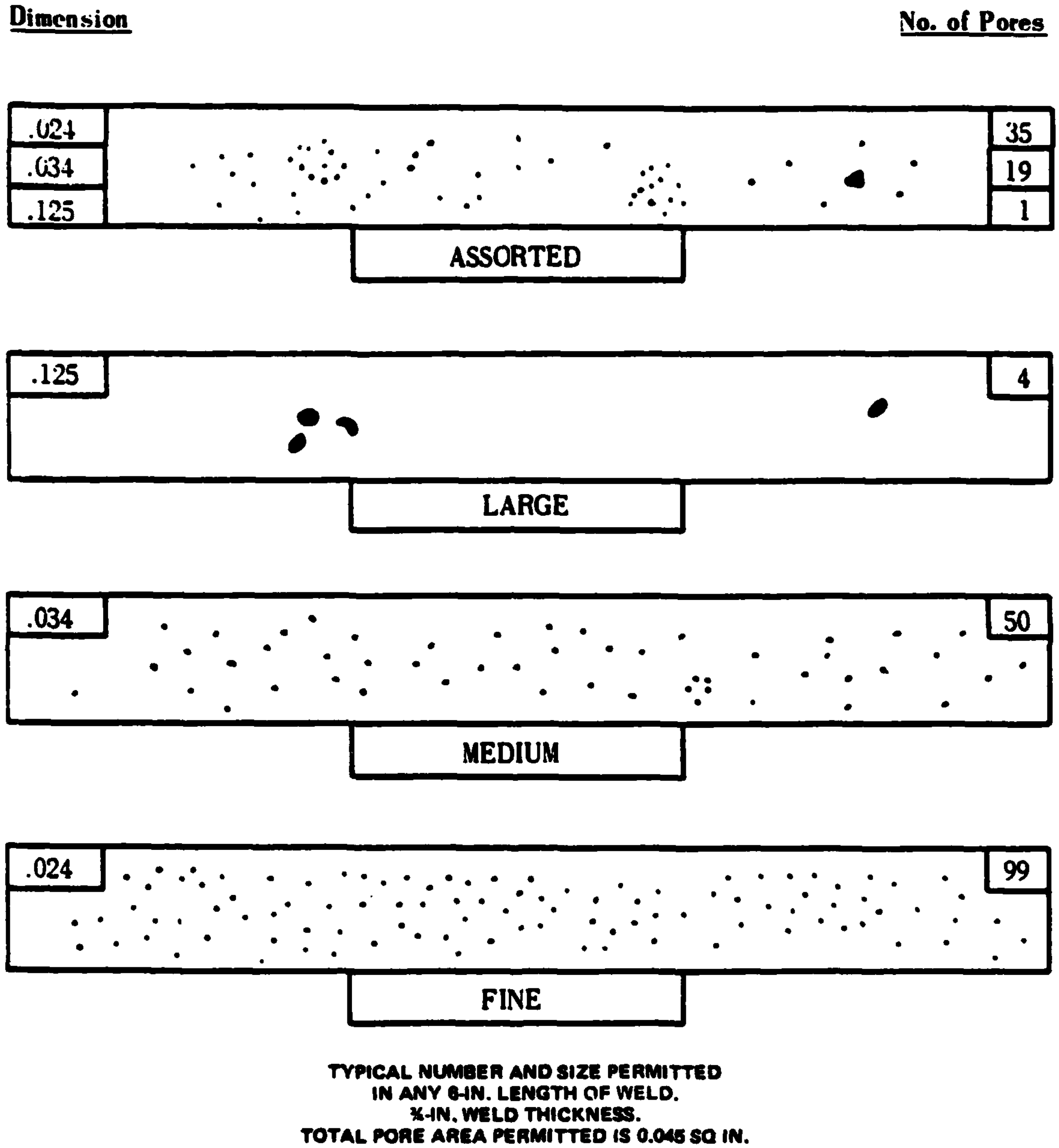


FIGURE 2 POROSITY CHARTS (A.S.M.E. BOILER AND PRESSURE VESSEL CODE)

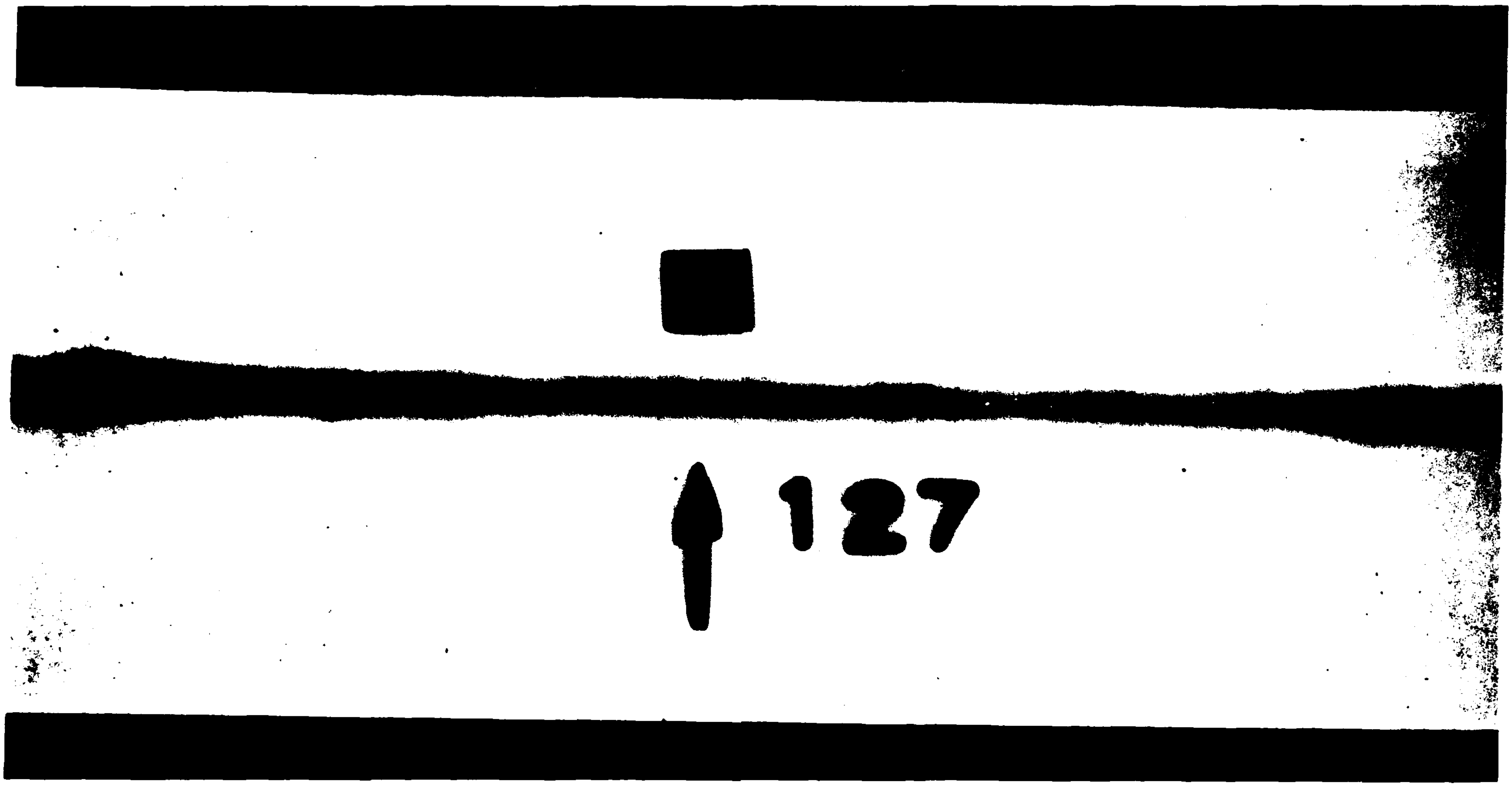


FIGURE 3 RADIOGRAPH OF CLEAR WELD (3/4 INCH PLATE)

FIGURE 4 RADIOGRAPH OF FINE PORES (3/4 INCH PLATE)

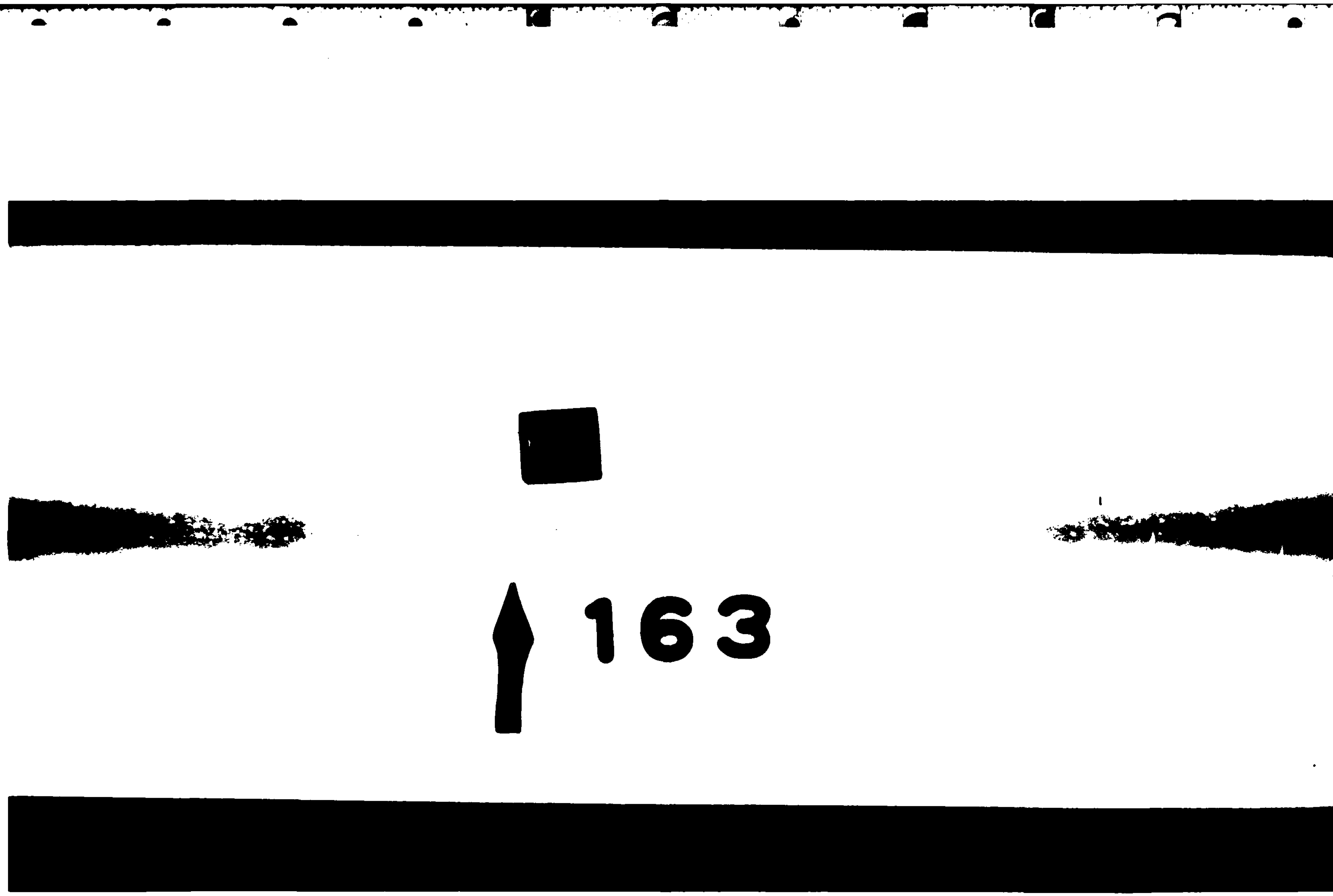


FIGURE 5 RADIOGRAPH OF MEDIUM PORES (3/4 INCH PLATE)

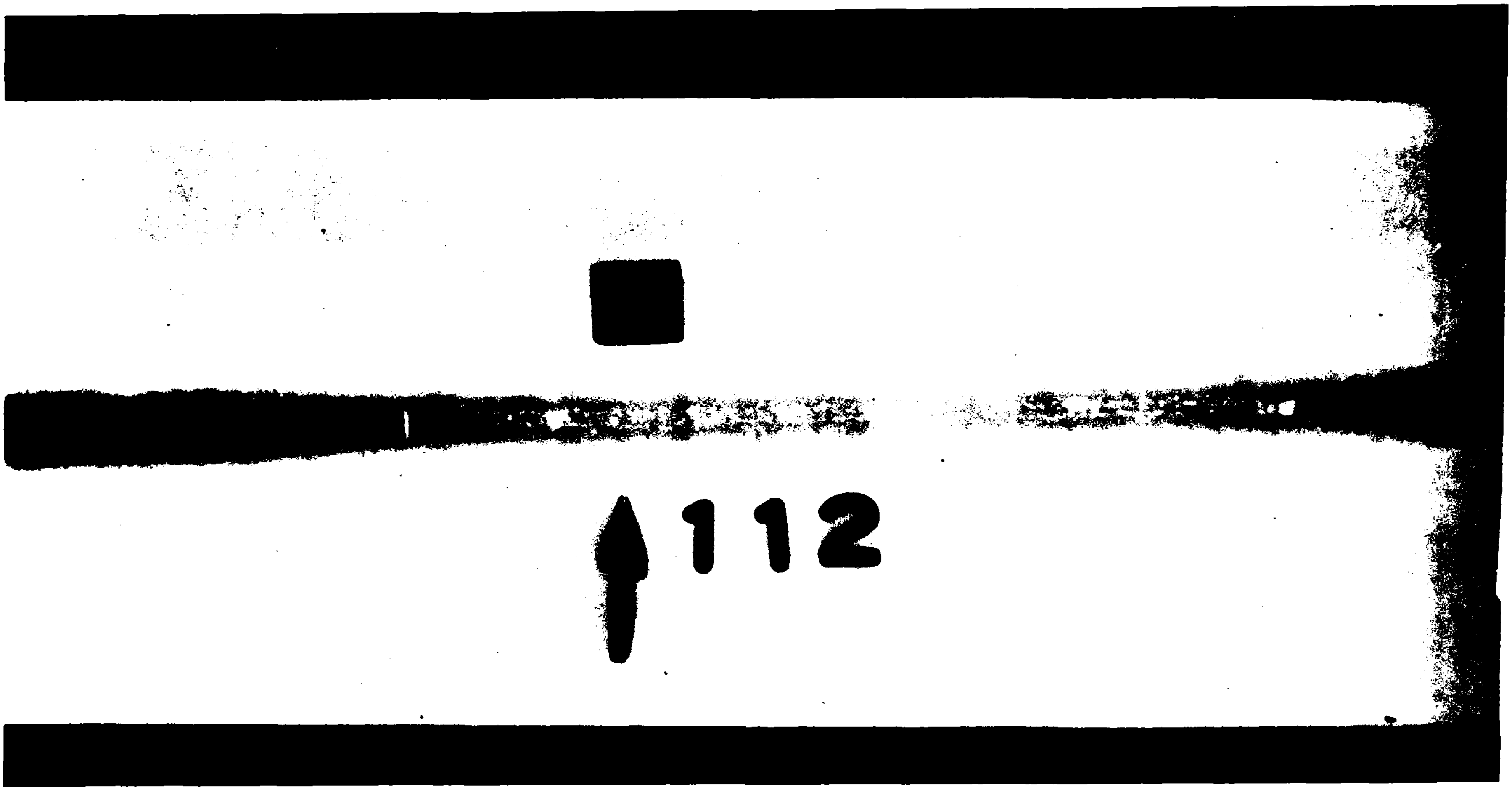


FIGURE 6 RADIOGRAPH OF ASSORTED PORES (3/4 INCH PLATE)

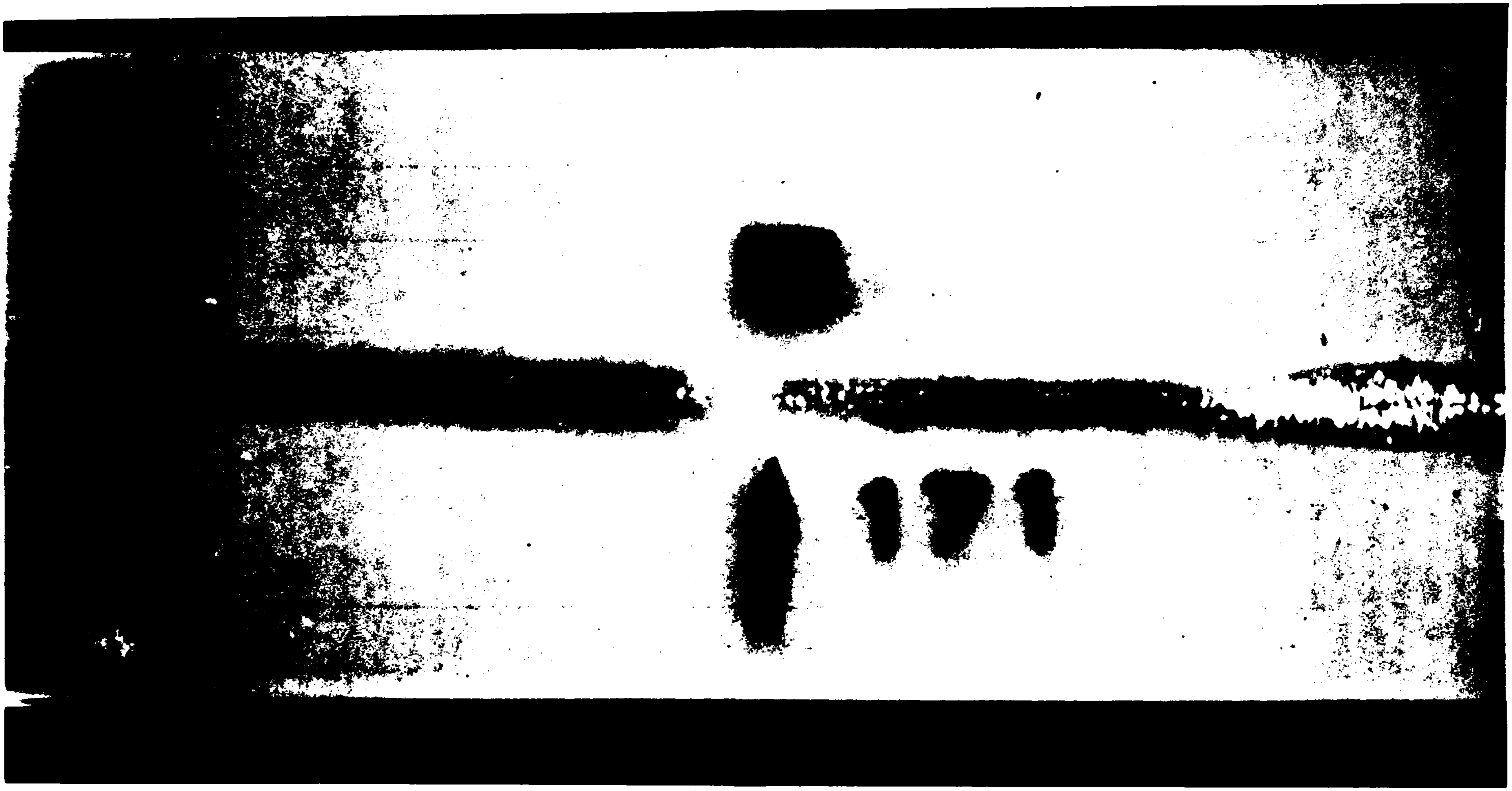


FIGURE 7 RADIOGRAPH OF LARGE PORES (3/4 INCH PLATE)

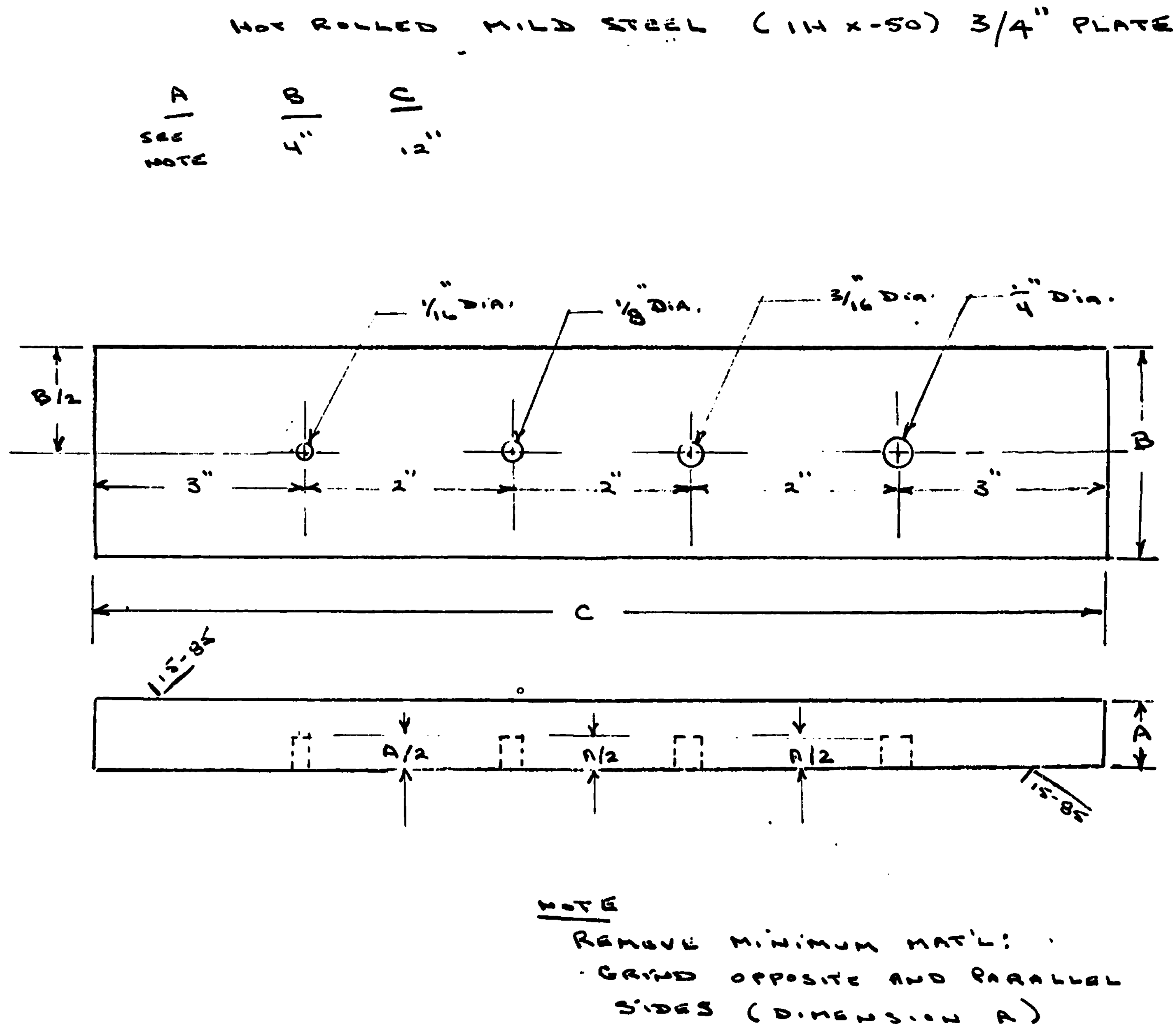


FIGURE 8 DIMENSION AND FLAT BOTTOM HOLE LOCATIONS IN ULTRASONIC REFERENCE CALIBRATION PLATE

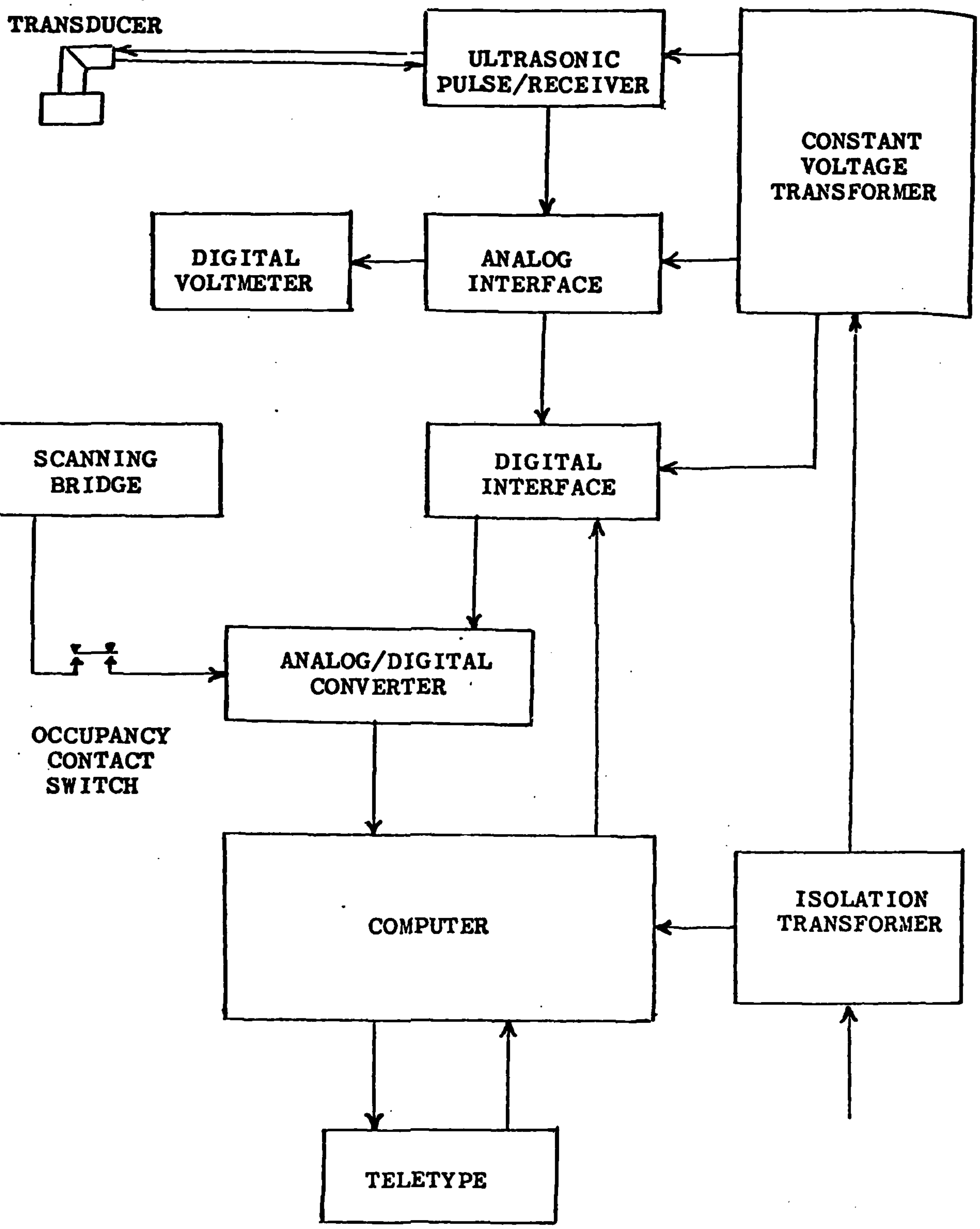


Figure 9 - Block Diagram of Computerized-Ultrasonic Inspection System for Quantitatively Rating Internal Soundness of 3/4" x 14" x 24" Weld Plates

HEAT OPERATOR

BILLET 132 DATE

COUPON

PASS

GATE

GAIN SETTING P. FACT SET # 4.0

CATAG	COUNT	FREQ	P. FACT.	PROD
1				
2				
3	1365	.0980	1.6	.1568
4	3498	.2511	2.6	.6530
5	3549	.2548	4.2	1.0529
6	1703	.1223	6.9	.8424
7	1137	.0816	11.2	.9110
8	873	.0627	18.1	1.1332
9	899	.0645	29.3	1.8898
10	420	.0302	47.4	1.4325
11	210	.0151	76.8	1.1586
12	138	.0099	124.5	1.2334
13	52	.0037	201.7	.7529
14	41	.0029	326.7	.9616
15	17	.0012	529.3	.6460
16	27	.0019	857.5	1.6622

TOTAL	13929			

STORED INDEX .0
CALCD INDEX 14.5 <--

Figure 10

HEAT OPERATOR

BILLET 135 DATE

COUPON

PASS

DATE

GAIN SETTING P. FACT SET # 4.0

GATING	COUNT	FREQ	P. FACT.	PROD
1	195	.0135	.6	.0083
2	12920	.8915	1.0	.8915
3	1023	.0706	1.6	.1143
4	244	.0168	2.6	.0441
5	129	.0075	4.2	.0320
6	2	.0001	6.9	.0010
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
TOTAL	14493			

STORED INDEX .0
CALCD INDEX 1.1 <--

Figure 11

HEAT OPERATOR

BILLET 151 DATE

COUPON

PASS

GATE

GAIN SETTING P. FACT SET = 4.0

CATEG	COUNT	FREQ	P. FACT.	PROD
1	1271	.0851	.6	.0528
2	8037	.5380	1.0	.5380
3	3866	.2588	1.6	.4193
4	971	.0650	2.6	.1703
5	454	.0324	4.2	.1292
6	135	.0124	6.9	.0853
7	146	.0098	11.2	.1091
8	8	.0005	18.1	.0097
9				
10				
11				
12				
13				
14				
15				
16				
TOTAL	14936			

STORED INDEX .0
CALCD INDEX 1.5 <--

Figure 12

HEAT OPERATOR

BILLET 162 DATE

COUPON

PASS

DATE

GAIN SETTING P. FACT SET = 4.0

CATEG	COUNT	FREQ	P. FACT.	PROD
1				
2	12368	.6721	1.0	.6721
3	5896	.3204	1.6	.5190
4	139	.0076	2.6	.0198
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
TOTAL	18403			

STORED INDEX .0
CALCD INDEX 1.2 <--

Figure 13

PART OPERATOR

BILLET 167 DATE

COUPON

PASS

GATE

GAIN SETTING P. FACT SET = 4.0

CATEG	COUNT	FREQ	P. FACT.	PROD
1				
2	4471	.2613	1.0	.2613
3	4162	.2429	1.6	.3923
4	6294	.3678	2.6	.9637
5	159	.0093	4.2	[illegible]
6	25	.0015	6.9	.0101
7	25	.0015	11.2	.0163
8	23	.0013	18.1	.0243
9	28	.0016	29.3	.0479
10	21	.0012	47.4	.0582
11	5	.0003	76.8	.0225
12	23	.0013	124.5	.1673
13	41	.0024	201.7	.4832
14	75	.0044	326.7	1.4320
15	67	.0039	529.3	2.0725
16	1732	.1012	857.5	86.7974
TOTAL	17111			

STORED INDEX .0
CALCD INDEX 92.8 <--

Figure 14

HEAT OPERATOR

BILLET 171 DATE

COUPON

PASS

GATE

GAIN SETTING P. FACT SET # 4.0

CATEG	COUNT	FREQ	P. FACT.	PROD
1	217	.0138	.6	.0086
2	6707	.4280	1.0	.4280
3	3762	.2401	1.6	.3889
4	2044	.1304	2.6	.3418
5	670	.0428	4.2	.1817
6	382	.0244	6.9	.1680
7	270	.0172	11.2	.1923
8	163	.0104	18.1	.1881
9	59	.0038	29.3	.1122
10	53	.0034	47.4	.1605
11	91	.0058	75.8	.4463
12	42	.0027	124.5	.3337
13	54	.0034	201.7	.6958
14	121	.0077	326.7	2.5227
15	127	.0081	529.3	4.2898
16	908	.0579	857.5	49.6879

TOTAL	15670			

STORED INDEX .0
CALCD INDEX 60.1 <--

Figure 15

HEAT OPERATOR

BILLET 119 DATE

COUPON

PASS

GATE

GAIN SETTING P. FACT SET = 4.0

CATEG	COUNT	FREQ	P. FACT.	PROD
1	265	.0147	.6	.0091
2	5067	.2805	1.0	.2805
3	4561	.2525	1.6	.4091
4	3388	.1876	2.6	.4915
5	2394	.1326	4.2	.5633
6	1001	.0554	6.9	.3819
7	583	.0323	11.2	.3602
8	511	.0283	18.1	.5115
9	146	.0081	29.3	.2367
10	123	.0068	47.4	.3231
11	22	.0012	76.8	.0936
12				
13				
14				
15				
16				

TOTAL	18061			

STORED INDEX .0
CALCD INDEX 3.7 <--

Figure 16

HEAT OPERATOR

BILLET /20 DATE

COUPON

PASS

DATE

GAIN SETTING P. FACT SET # 4.0

CHANS	COUNT	FREQ	P. FACT.	PROD
1				
2	2756	.1795	1.0	.1795
3	4625	.3012	1.6	.4880
4	4636	.3020	2.6	.7860
5	1994	.1299	4.2	.5519
6	570	.0371	6.9	.2558
7	414	.0270	11.2	.3029
8	289	.0188	18.1	.3423
9	80	.0052	29.3	.1526
10	20	.0013	47.4	.0618
11				
12				
13				
14				
15				
16				

TOTAL	15354			

STORED INDEX .0
CALCD INDEX 3.1 <--

Figure 17

HEAT OPERATOR

BILLET 138 DATE

COUPON

PASS

DATE

GAIN SETTING P. FACT SET = 4.0

CATEG	COUNT	FREQ	P. FACT.	PROD
1	4095	.2552	.6	.1532
2	3162	.1836	1.0	.1836
3	2053	.1192	1.6	.1931
4	787	.0457	2.6	.1197
5	574	.0333	4.2	.1417
6	551	.0320	6.9	.2205
7	319	.0185	11.2	.2207
8	316	.0180	18.1	[illegible]
9	383	.0222	29.0	.6512
10	394	.0229	47.4	1.0854
11	300	.0174	76.0	[illegible]
12	[illegible]	[illegible]	124.5	1.5192
13	238	.2138	201.7	2.7874
14	303	.0176	326.7	5.7456
15	191	.0111	529.3	5.8789
16	3052	.1771	857.5	151.8800
TOTAL	17220			

STORED INDEX .0
CALCD INDEX 172.4 <--

Figure 18

HEAT OPERATOR

BILLET 159 DATE

COUPON

PASS

GATE

GAIN SETTING P. FACT SET : 4.0

CATEG	COUNT	FREQ	P. FACT.	PROB
1				
2				
3	1011	.0539	1.6	.0872
4	3855	.2053	2.6	.5382
5	4453	.2372	4.2	1.0081
6	3467	.1847	6.9	1.2724
7	2007	.1069	11.2	1.1931
8	1580	.0842	18.1	1.5217
9	1383	.0737	29.3	2.1570
10	467	.0249	47.4	1.1801
11	305	.0162	76.8	1.2486
12	98	.0052	124.5	.6499
13	125	.0067	201.7	1.3429
14	22	.0012	326.7	.3829
15				
16				
TOTAL	18773			

STORED INDEX .0
CALCD INDEX 12.6 <--

Figure 19

HEAT OPERATOR

BILLET 158 DATE

COUPON

PASS

DATE

GAIN SETTING P. FACT SET = 4.0

CATEG	COUNT	FREQ	P. FACT.	PROD
1				
2	339	.0207	1.0	.0207
3	1303	.0797	1.6	.1291
4	2321	.1419	2.6	.3718
5	1617	.0989	4.2	.4202
6	2423	.1482	6.9	1.0228
7	1616	.0988	11.2	1.1328
8	1567	.0958	18.1	1.7324
9	1275	.0780	29.3	2.2827
10	1159	.0709	47.4	3.3620
11	990	.0605	76.8	4.6522
12	674	.0412	124.5	5.1306
13	493	.0301	201.7	6.0797
14	198	.0121	326.7	3.9554
15	238	.0146	529.3	7.7029
16	141	.0086	857.5	7.3931

TOTAL	16354			

STORED INDEX .0
CALC INDEX 45.4 <--

Figure 20

HEAT OPERATOR

BILLET /62 DATE

COUPON

PASS

DATE

GAIN SETTING P. FACT SET ; 4.0

CATEG	COUNT	FREQ	P. FACT.	PROD
1				
2	492	.0254	1.0	.0254
3	2572	.1326	1.6	.2148
4	3707	.1911	2.6	.5006
5	3238	.1669	4.2	.7093
6	2190	.1129	6.9	.7777
7	1566	.0807	11.2	.9088
8	1086	.0560	18.1	1.0121
9	914	.0471	29.3	1.3794
10	472	.0243	47.4	1.1542
11	336	.0173	76.8	1.3309
12	483	.0249	124.5	3.0993
13	296	.0153	201.7	3.0770
14	295	.0153	325.7	4.9844
15	426	.0220	529.3	11.6222
16	1327	.0684	857.5	58.6517

TOTAL	19421			

STORED INDEX .0
CALCD INDEX 89.4 <--

Figure 21

HEAT OPERATOR

BILLET /77 DATE

COUPON

PASS

DATE

GAIN SETTING P. FACT SET # 4.0

CATEG	COUNT	FREQ	P. FACT.	PROD
1				
2	1635	.1051	1.0	.1051
3	4744	.3051	1.6	.4942
4	3236	.2100	2.6	.5523
5	2033	.1307	4.2	.5556
6	1256	.0808	6.9	.5565
7	391	.0251	11.2	.2806
8	314	.0202	18.1	.3651
9	209	.0134	29.3	.3935
10	306	.0197	47.4	.9335
11	335	.0215	76.8	1.6556
12	113	.0073	124.5	.9047
13	63	.0041	201.7	.8171
14	109	.0070	326.7	2.2901
15	101	.0064	529.3	4.4591
16	645	.0415	857.5	35.5693

TOTAL	15550			

STORED INDEX .0
CALC. INDEX 49.9 <--

Figure 22

HEAT OPERATOR

BILLET 182 DATE

COUPON

PASS

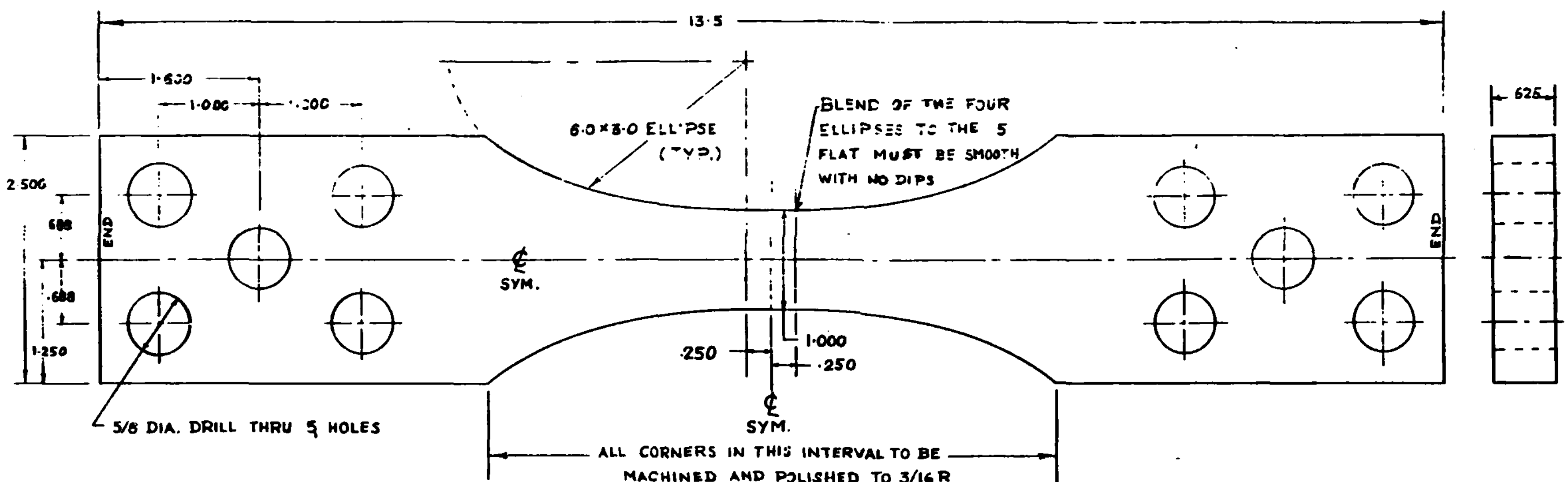
DATE

GAIN SETTING P. FACT SET , 4.0

CATEG	COUNT	FREQ	P. FACT.	PROD
1	12256	.6543	.6	.3437
2	2657	.1465	1.0	.1465
3	1874	.1033	1.6	.1673
4	843	.0465	2.6	.1217
5	421	.0232	4.2	.0956
6	494	.0272	6.9	.1876
7	171	.0094	11.2	.1052
8	114	.0063	18.1	.1136
9	49	.0027	29.3	.0791
10	15	.0008	47.4	.0392
11	17	.0009	76.8	.0720
12	18	.0010	124.5	.1235
13	24	.0013	201.7	.2665
14	22	.0012	326.7	.3962
15	41	.0023	529.3	1.1962
16	1326	.0731	857.5	62.6747
TOTAL	18142			

STORED INDEX .0
CALC INDEX 66.1 <--

Figure 23



NOTES: 1. Finish all surfaces except ends to 32 RMS
2. Shot peen ground and polished samples to: (Mask the holes during shot peening)

Intensity..... 0.013A
Coverage...... 100%
Shot No....... SAE S230

FIGURE 24 UNIAXIAL FATIGUE SPECIMEN

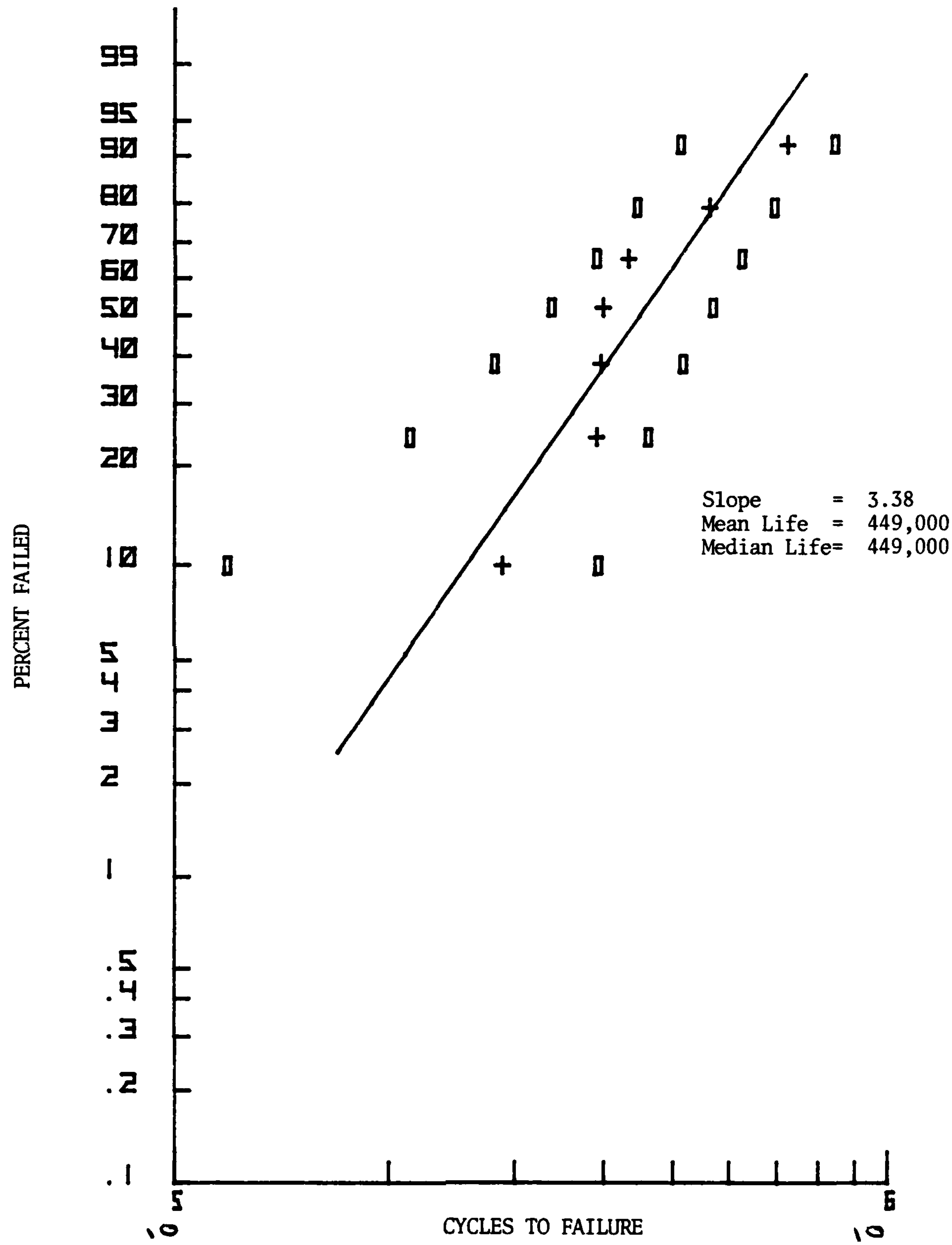


FIGURE 25 UNIAXIAL FATIGUE TESTS OF IH-50X (BASE MATERIAL)

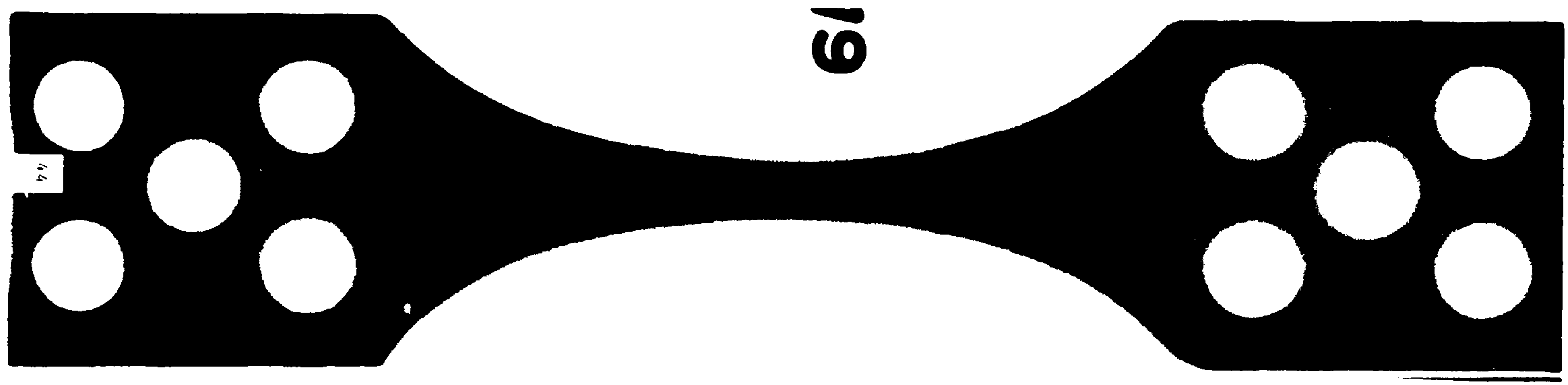


FIGURE 26 RADIOGRAPH OF FATIGUE SPECIMEN (CLEAR WELD)

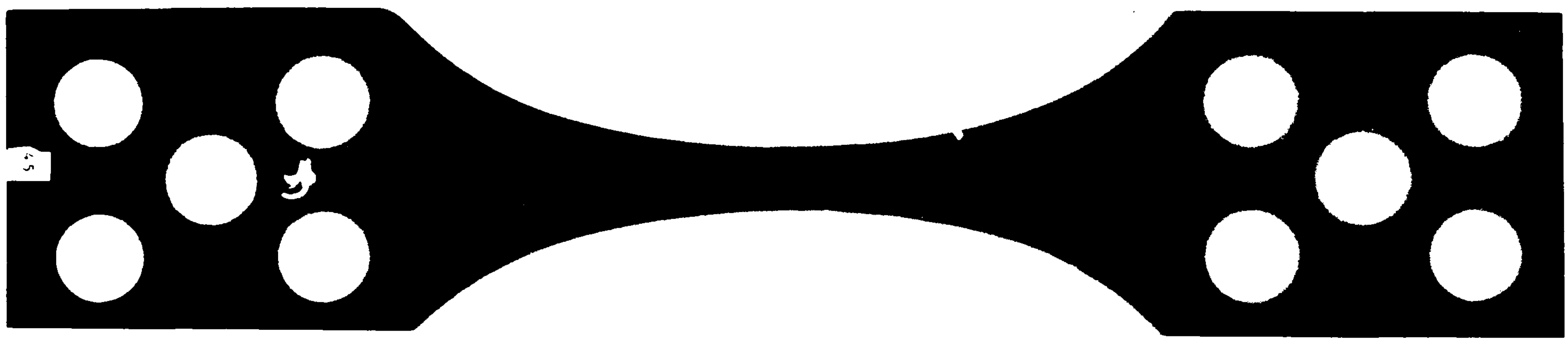


FIGURE 27 RADIOGRAPH OF FATIGUE SPECIMEN (FINE POROSITY)

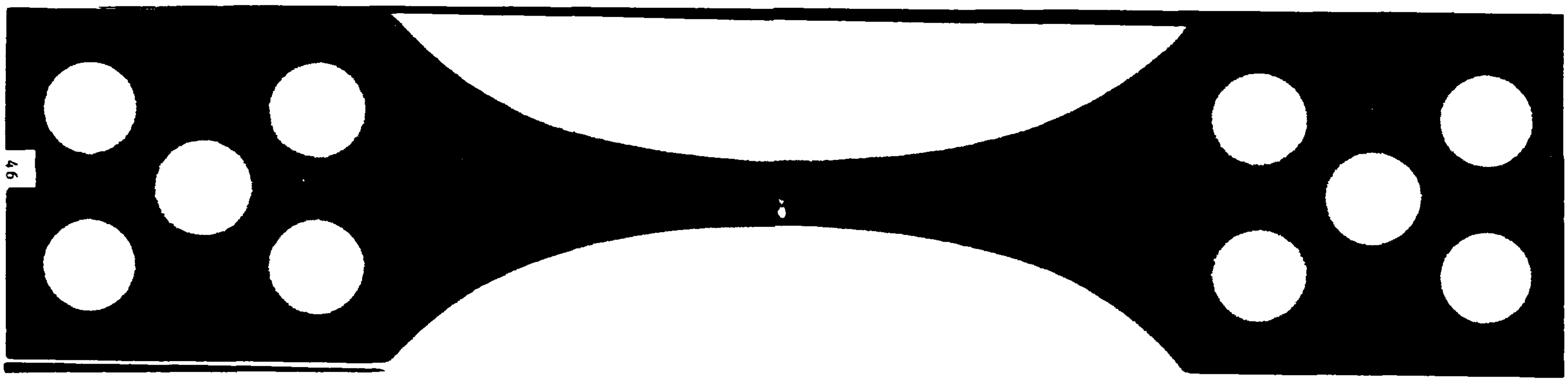


FIGURE 28 RADIOGRAPH OF FATIGUE SPECIMEN (LARGE POROSITY)

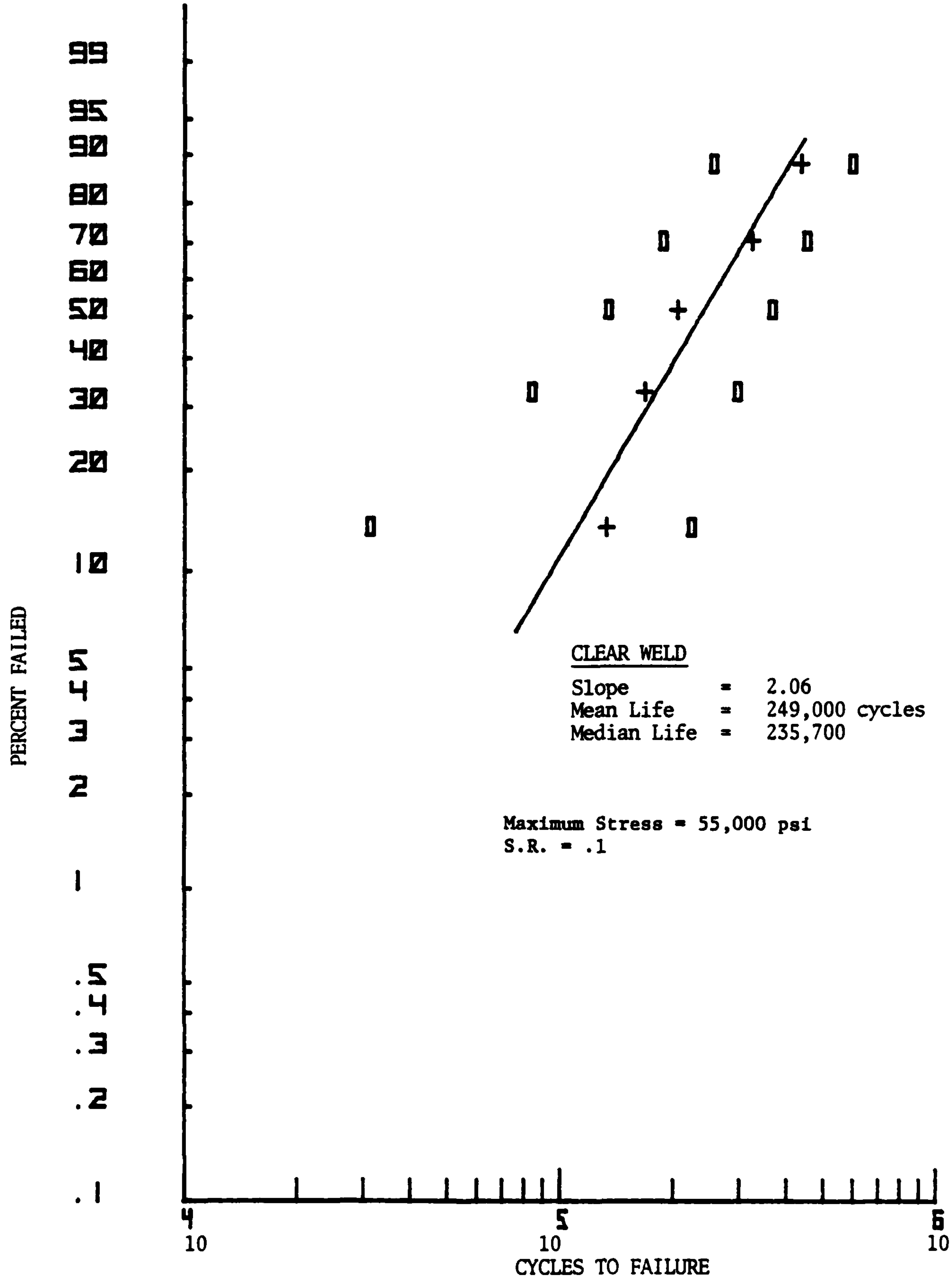


Figure 29 Uniaxial Fatigue Tests of IH-50X with Clear Weld

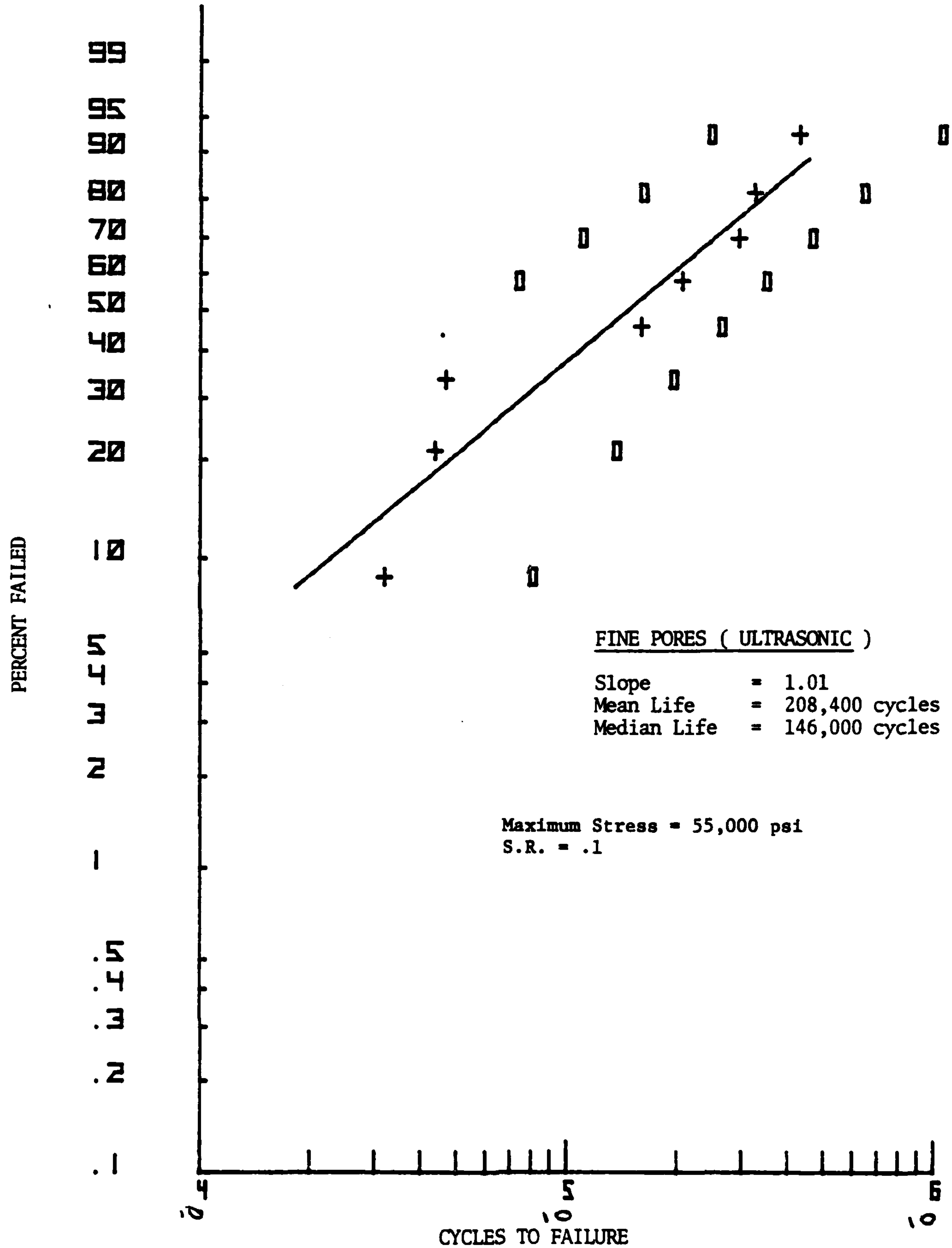


Figure 30 Uniaxial Fatigue Tests of IH-50X with Fine Pore Weld

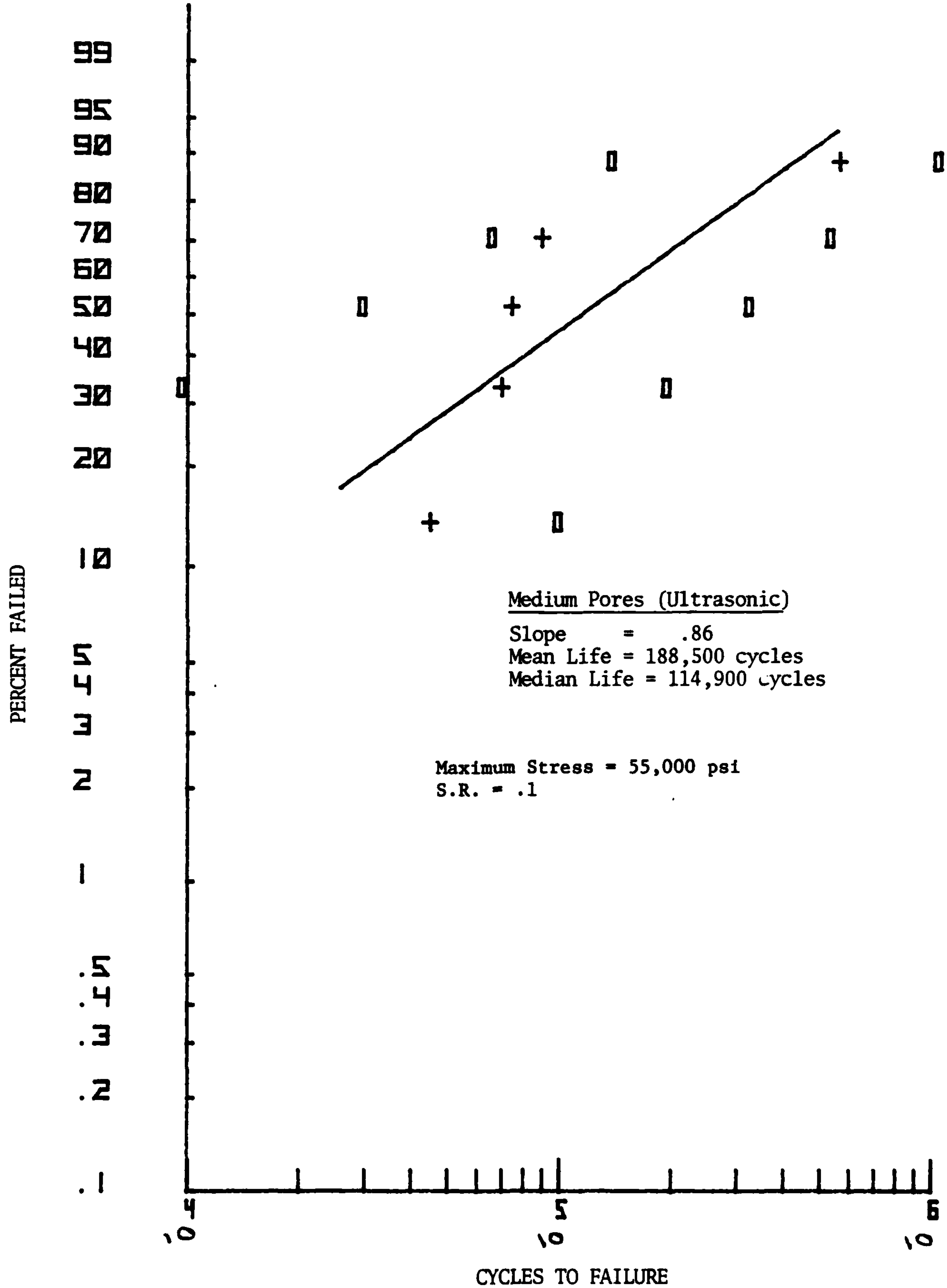


Figure 31 Uniaxial Fatigue Tests of IH-50X with Medium Pore Weld

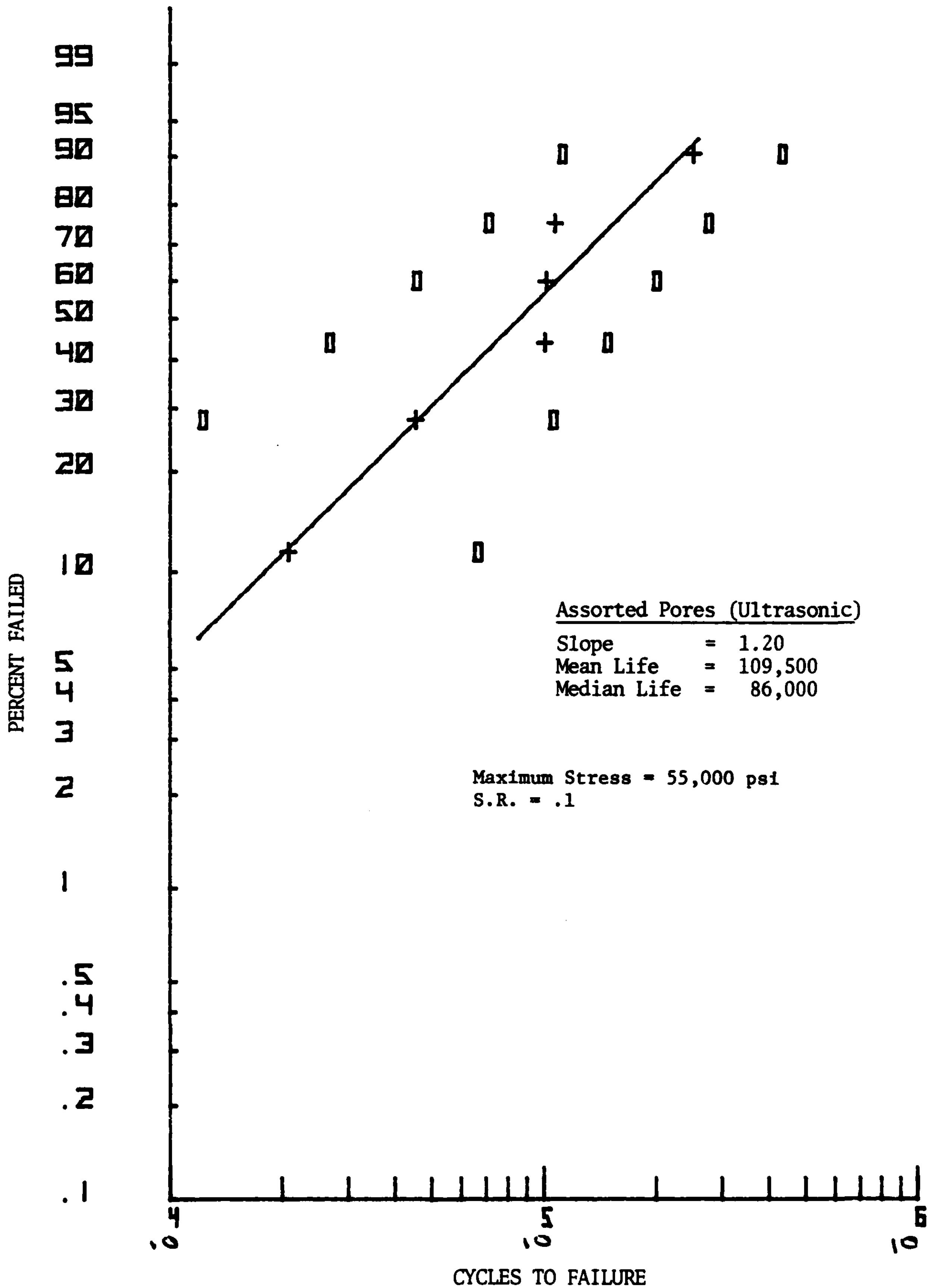


Figure 32 Uniaxial Fatigue Tests of IH-50X with Assorted Size Pores in Weld Zone

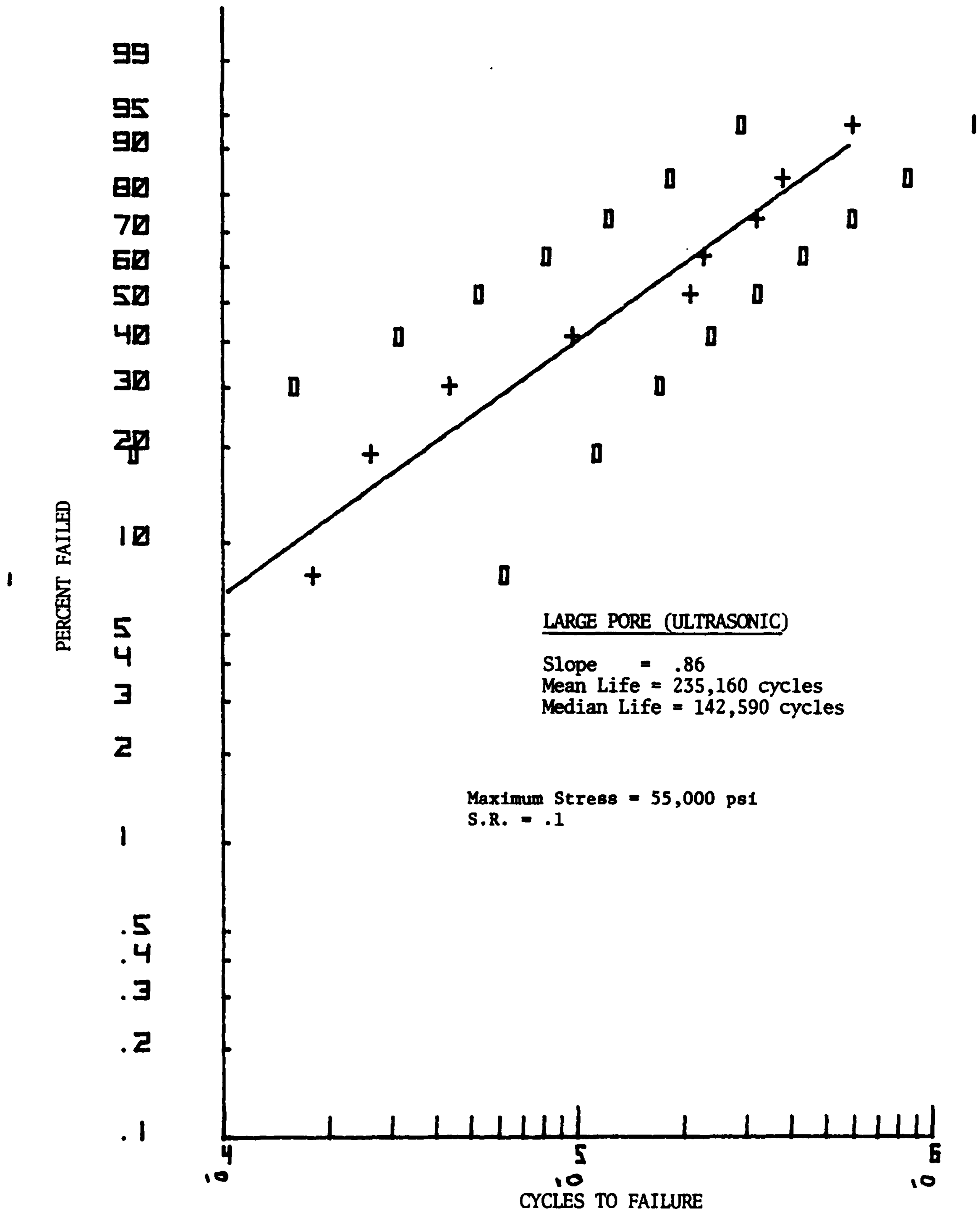


FIGURE 33 UNIAXIAL FATIGUE TESTS OF IH-50X WITH LARGE SIZE PORES IN WELD ZONE

FIGURE 34 FRACTURED (THRU WELD ZONE) IH 50-X FATIGUE SPECIMEN

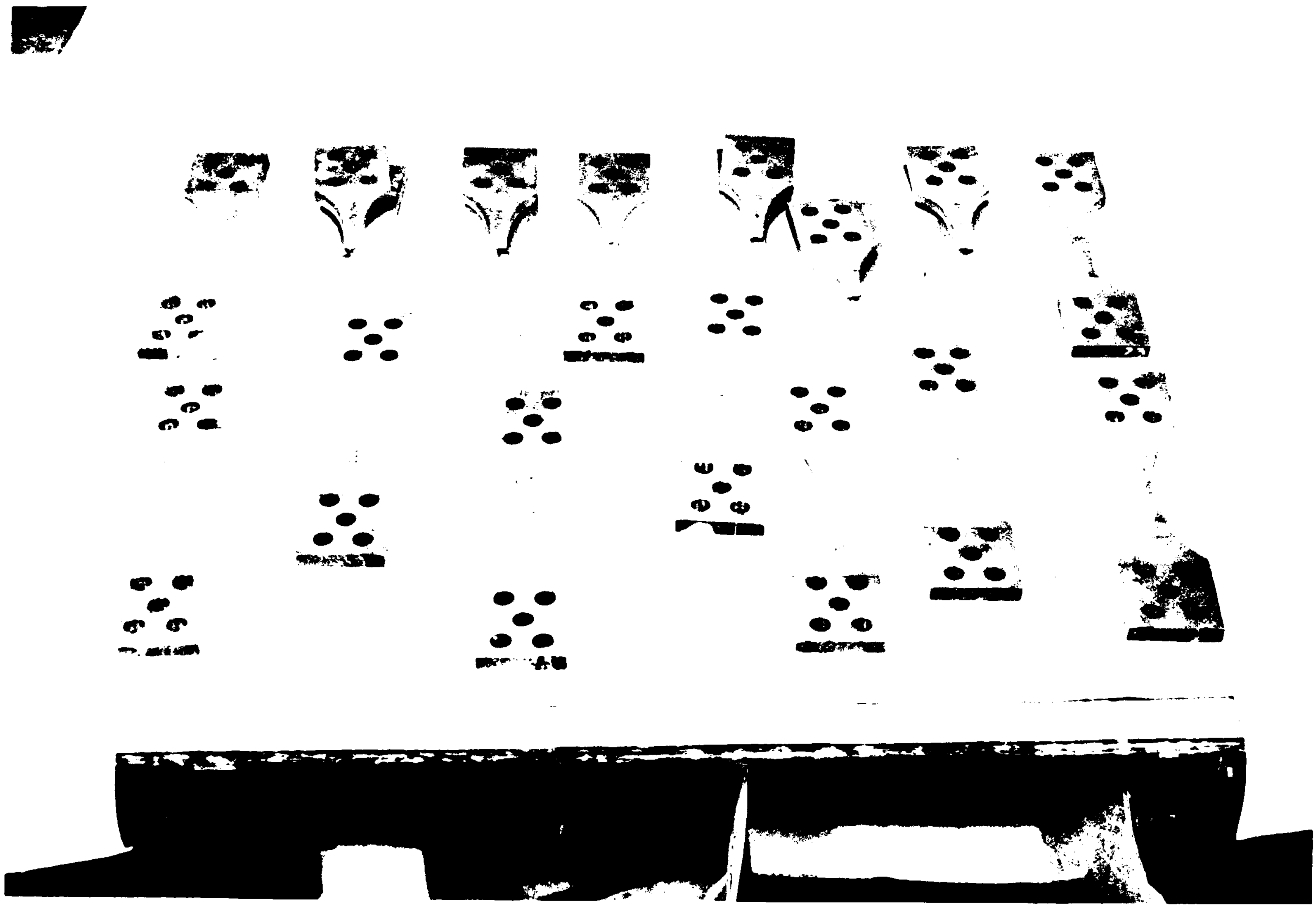


FIGURE 35 REPRESENTATIVE SELECTION OF FRACTURED FATIGUE SPECIMENS

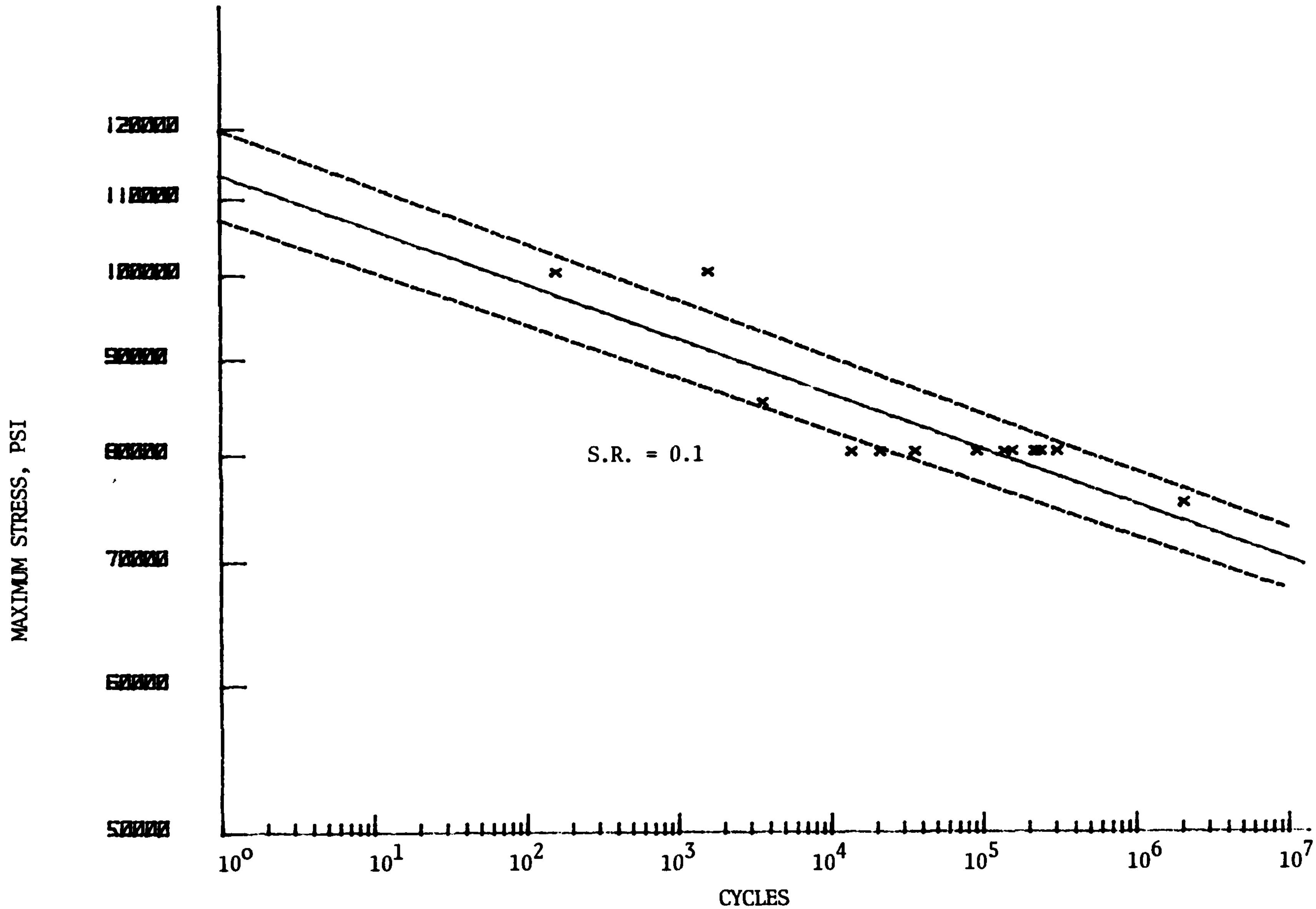


FIGURE 36 UNIAXIAL FATIGUE OF ARMOR STEEL WITH WELD ZONE CONTAINING VARIOUS PORE SIZES

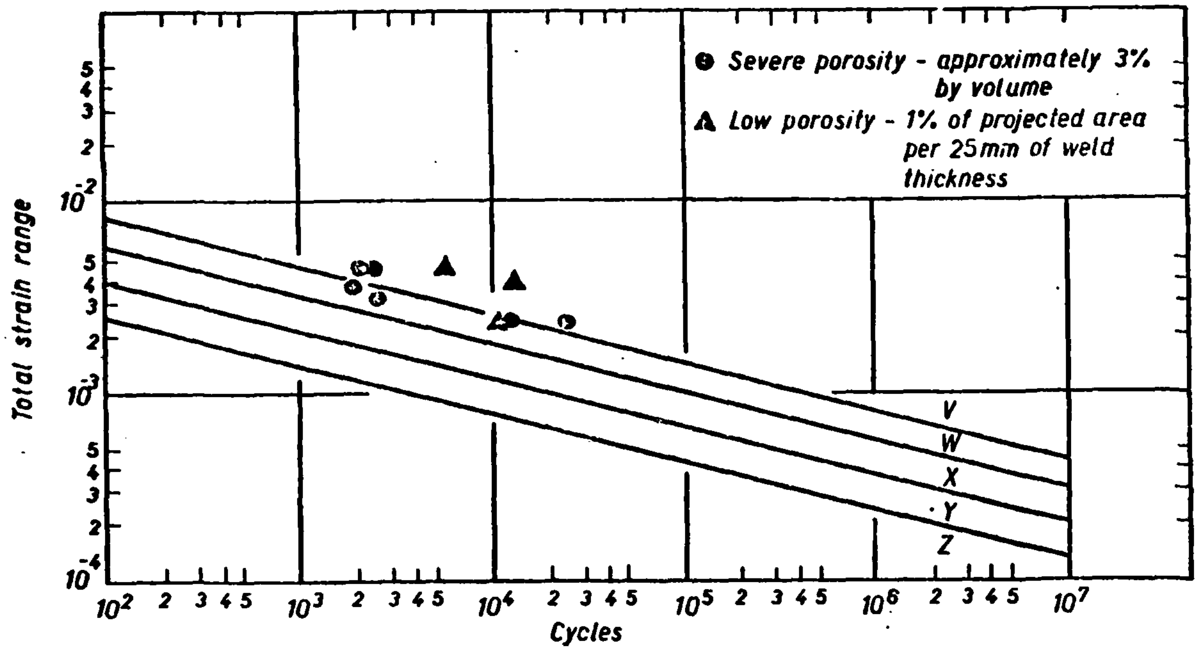


FIGURE 37 RESULTS (C.F. BOULTON) OF TESTS ON FATIGUE SPECIMENS CONTAINING POROSITY DEFECTS

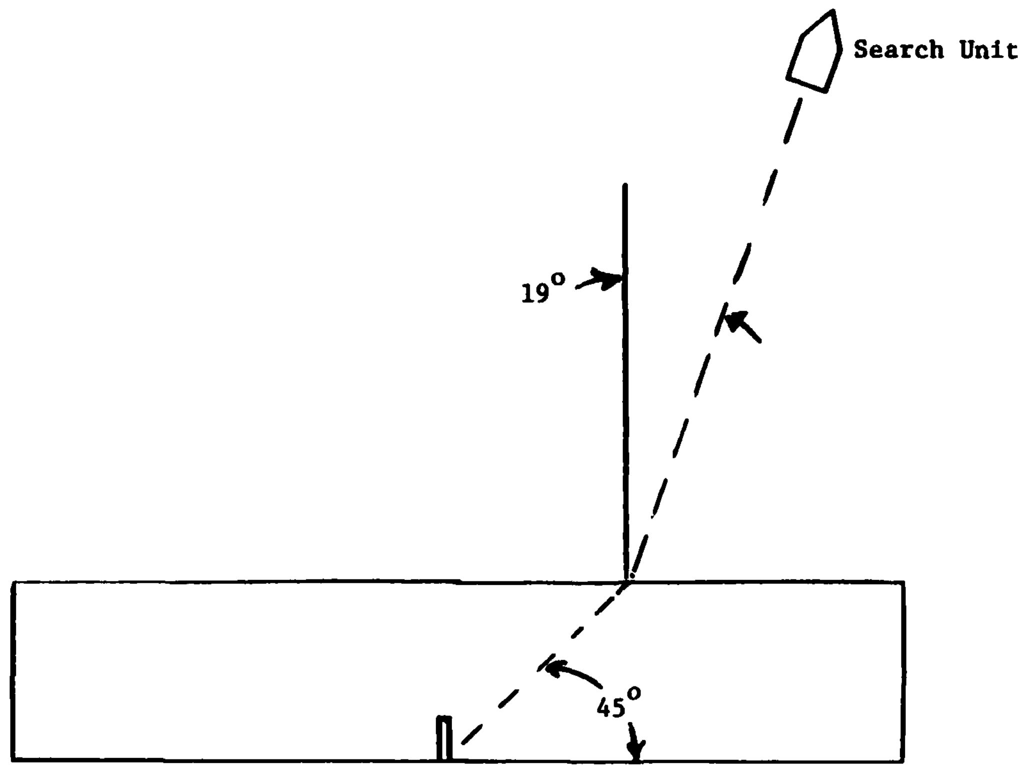


Figure 38. Position of Search Unit with Reference to Flat Bottom Hole for Angle Beam (45°) Ultrasonic Calibration

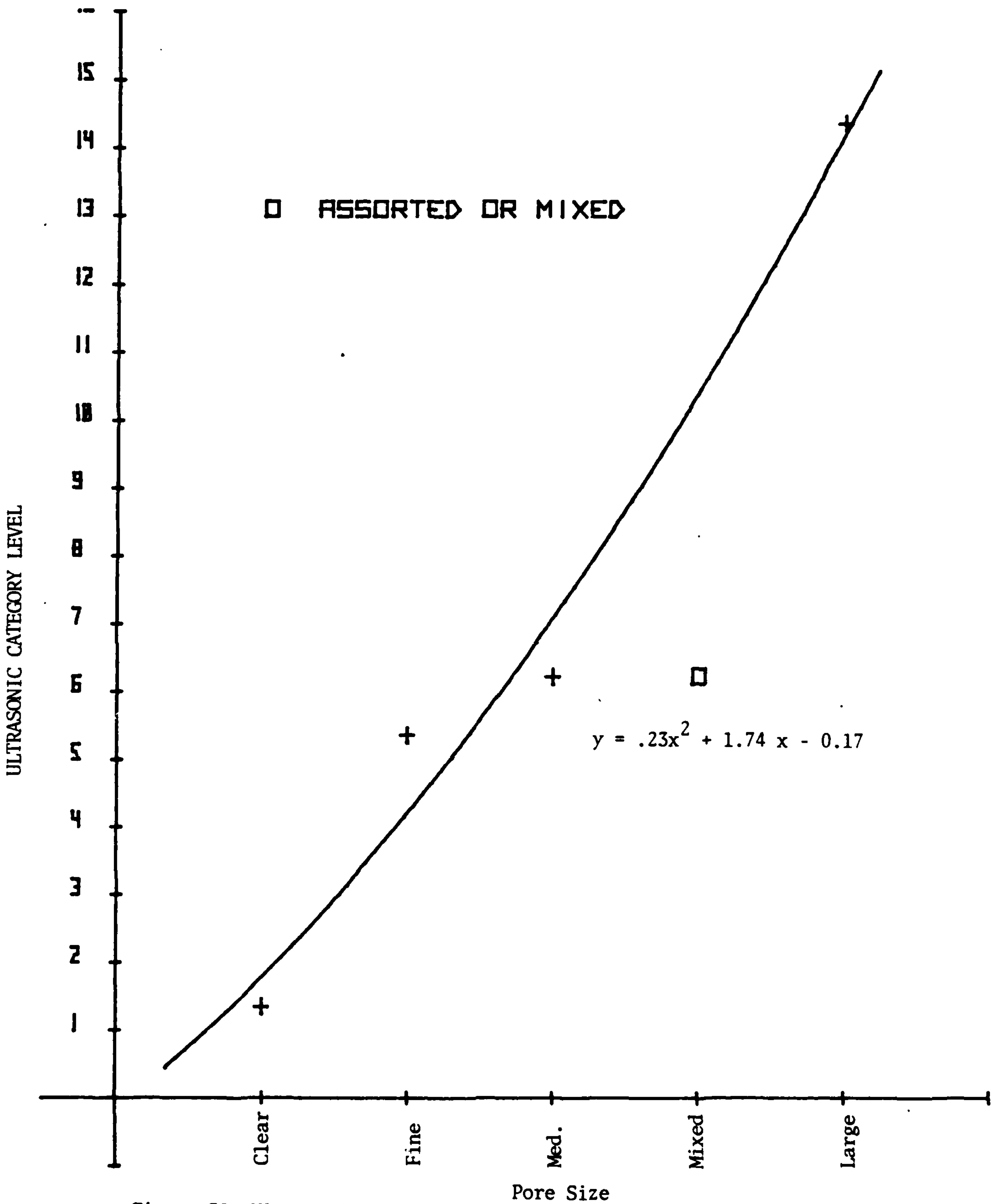


Figure 39 Ultrasonic Category Level Versus Pore Size (Initial Calibration with 1/8 inch Diameter Flat Bottom Hole)

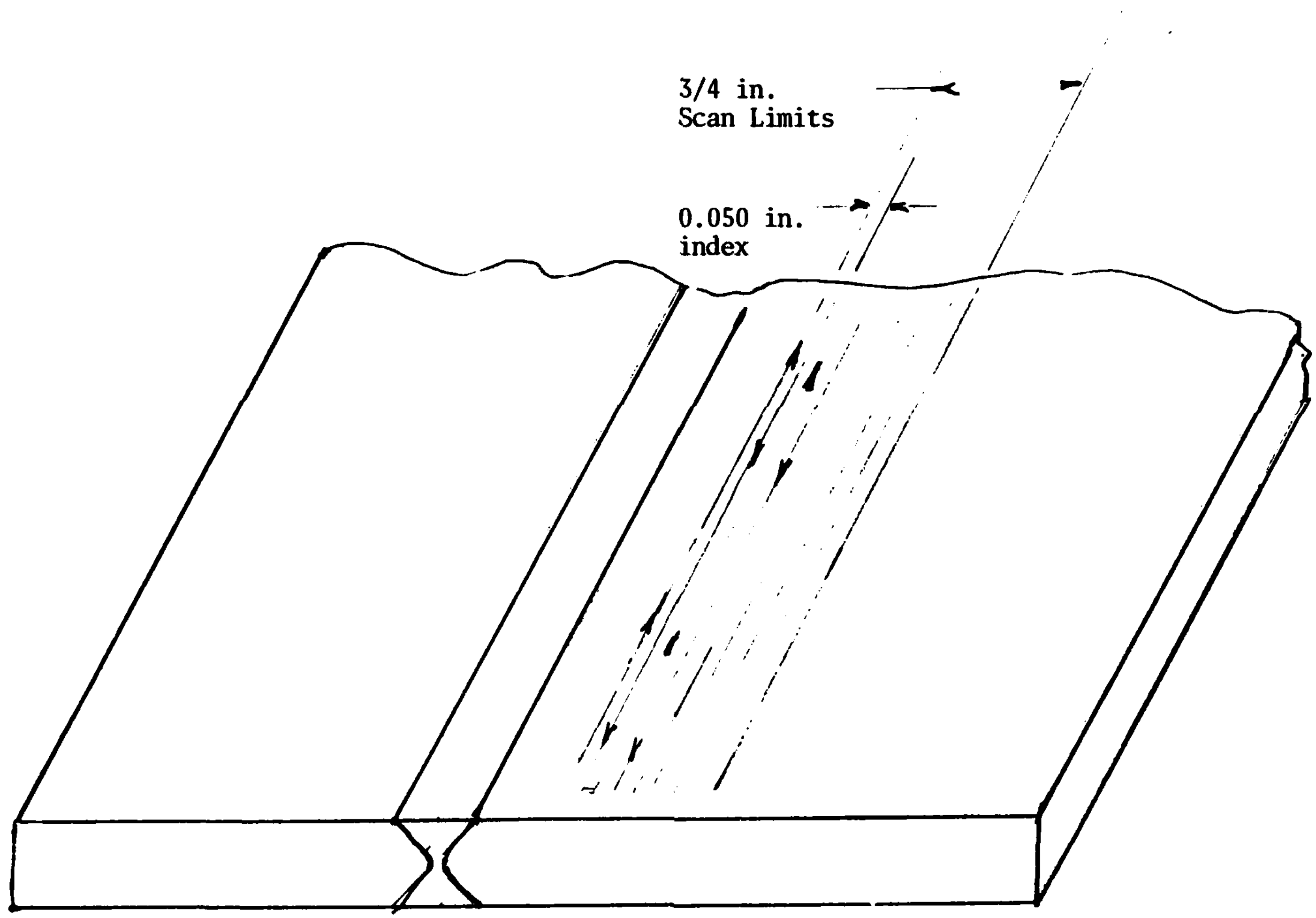


Figure 40 Ultrasonic Scan Pattern for Immersed Angle Beam (45^{o}) Inspection of Weld Zone for 3/4 Inch Thick Plate

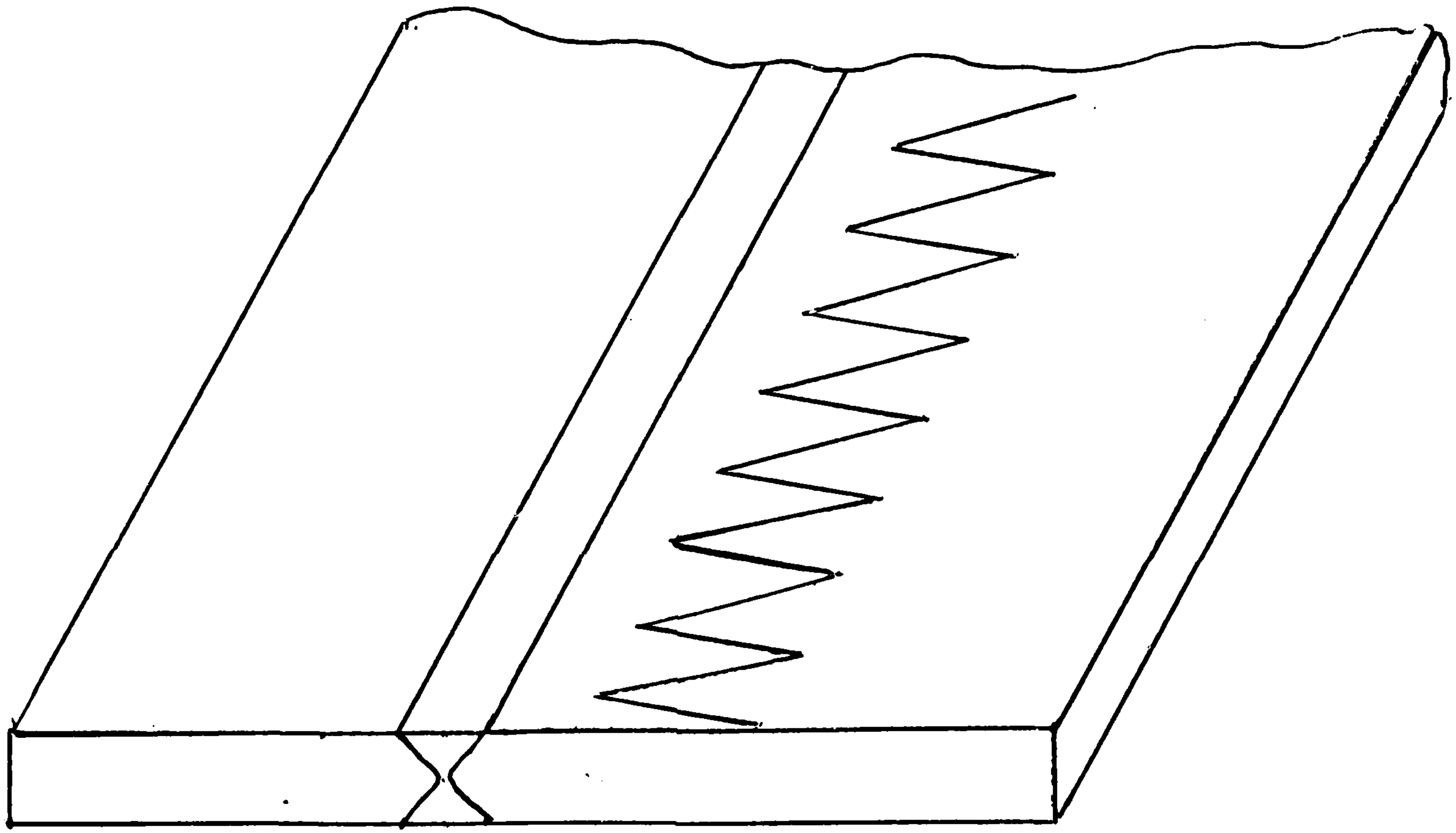


Figure 41 Saw Cut Scan Pattern of Weld Inspection Using a Contact Angle Beam (45°) Search Unit

TABLE I

WELDING CONDITIONS FOR VARIOUS LEVELS OF POROSITY

Porosity Level	Plate No.	Wire Feed Rate (ipm)(b)		Voltage		Travel Speed (ipm)		Shielding Gas (a)	
		Root Pass	Top Pass	Root Pass	Top Pass	Root Pass	Top Pass	Root Pass	Top Pass
Water Clear	175	390	390	28	30	17.0	14.5	75-25	75-25
	135	390	390	29	29	17.0	13.0	75-25	75-25
	151	360	360	26	28	26.0	11.0	75-25	98-2
	160	360	360	26	28	26.0	10.0	75-25	98-2
Fine	119	390	390	26	30	16.0	13.5	75-25	98-2(30)
	132	360	360	26	27	22.0	13.5	75-25	98-2(65)
	138	360	430	26	28	23.5	13.5	75-25	98-2(25)
	151	360	400	26	28	24.5	11.0	75-25	98-2
	163	360	490	26	29	26.5	12.5	75-25	98-2(25)
	167	360	490	26	29	26.5	12.0	75-25	98-2
Medium	158	360	360	26	28	26.5	10.0	75-25	98-2
	161	360	440	26	29	25.0	12.0	75-25	98-2(22)
	158	360	330	26	27	26.5	10.0	75-25	98-2
	122	360	330	26	27	26.5	10.0	75-25	98-2
Assorted	147	390	390	26	28	16.0	13.0	75-25	98-2(30)
	138	390	460	26	28	17.5	14.0	75-25	98-2(30)
	132	360	360	26	27	21.0	13.5	75-25	98-2(65)
	135	360	360	26	27	23.5	12.0	75-25	98-2(75)
	159	360	360	27	28	25.0	10.0	75-25	98-2
	169	360	460	26	28	26.5	13.5	75-25	98-2(25)
	162	360	470	26	29	26.5	12.0	75-25	98-2(25)
Large	139	360	560	26	29	26.5	14.5	75-25	98-2(25)
	180	360	540	26	29	26.5	14.5	75-25	98-2(25)
	182	360	540	26	29	24.5	13.5	75-25	98-2(25)
	152	360	530	26	29	26.5	14.5	75-25	98-2(25)

NOTES:

(a) 75-25 = Argon + 25% CO_2, 98-2 = Argon + 2% O_2
Gas flow was 35 C.F.H., unless otherwise specified in brackets

(b) Wire diameter: 0.045 inch

TABLE II

ULTRASONIC POROSITY RATING OF VARIOUS WELD PLATES

IH-50X

Plate No.	Ultrasonic Rating (Porosity Level)
119	3.7
120	3.1
135	1.1
151	1.5
159	12.6
132	14.5
171	60.1
177	49.9
167	92.8
158	45.4
182	66.1
138	172.4
114	3.3
115	3.8
116	84.6
117	3.7
118	3.0
121	2.4
122	11.7
123	4.1
124	10.5
180	208.3
139	87.3
163	52.4
147	14.0
127	1.7
152	15.5

ARMOR PLATE

Plate No.	Ultrasonic Rating (Porosity Index)
A-1	2.2
A-2	2.3
A-3	13.6
A-4	24.4
A-5	
A-6	3.1
A-7	92.1
A-8	21.5
A-9	26.3
A-10	44.1
A-11	2.2

TABLE III

VARIATION IN ULTRASONIC INSPECTION TECHNIQUE FOR MAXIMUM RESPONSE FROM WELD DEFECT (PORE)

Plate No. 116

Pore Ident.	Instrument Gain Setting	Response Voltage Immersion	Response Voltage Contact Angle Beam
1	14	10.98	12.0+
1	25	4.90	6.67
2	14	10.45	12.0+
2	25	4.90	12.0
3	14	10.27	12.0+
3	25	4.90	7.68
4	25	4.90	6.20
5	25	4.90	8.83

(12.0 + voltage represent saturated video signal)

TABLE IV

RESPONSE SENSITIVITY FROM
VARIOUS LARGE PORES IN
WELD PLATE USING IMMERSION
AND ANGLE BEAM CONTACT
ULTRASONIC INSPECTION METHOD

Plate No. 184

Pore Ident.	Instrument Gain Setting	Response Voltage Immersion	Response Voltage Contact Angle Beam
1	14	9.68	Saturated
1	25	4.90	11.09
1	33	2.45	6.05
2	14	8.14	Saturated
2	25	4.90	Saturated
2	33	2.45	9.15
3	14	8.93	Saturated
3	25	4.90	11.60
3	33	2.45	8.25
4	14	12.25	Saturated
4	25	4.90	10.19
4	33	2.45	4.59

TABLE V

UNIAXIAL FATIGUE RESPONSE
OF IH-50X BASE SPECIMENS
(S.R. - 0.1, MAXIMUM STRESS = 55,000PSI)

Spec. No.	Cycles to Failure
3B	711,000
4B	552,000
5B	388,000
6B (49,000 psi max.)	4,710,000 (runout)
7B	423,900
8B	390,700
9B	383,100
10B	283,000

TABLE VI

UNIAXIAL FATIGUE TEST OF
IH-50X WELD SPECIMENS WITH
VARIOUS POROSITY LEVELS
(RADIOGRAPHIC) WITH 55,000 psi
MAXIMUM STRESS, S.R.=0.1

Sample No.	Plate No.	Ultrasonic Category	Cycles to Failure
		CLEAR	
8	127	.6	161,800
27	127	4	86,300
34	135	.8	312,000
2	151	1	198,200
35	151	1	128,000
36	135	.8	421,500
		FINE	
33	110	2	312,300
6	162	3	42,900
12	158	11.2	242,600
18	147	3	153,400
21	121	5	71,500
25	163	8	97,600
		MEDIUM	
13	152	11.4	201,400
17	147	2.5	30,700
20	158	10	96.800
24	152	6.5	43,300
3	122	2	198,000
37	167	2	413,300

TABLE VI (Cont)

Sample No.	Plate No.	Ultrasonic Category	Cycles to Failure
		LARGE	
15	139	14.5	365,900
10	139	13.5	575,700
4	116	14	17,300
22	152	16	220,100
16	119	13	25,200
14	139	16	309,000
38	116	15	42,000
41	114	13	93,400
		ASSORTED	
39	182	7	67,200
19	132	5	1,132,500
5	138	8	20,600
7	147	2	282,100
11	163	2	45,000
26	132	7	543,700
40	182	9	103,200
42	159	10	43,700

TABLE VII

WEIBULL PARAMETERS FOR IH-50X
UNIAXIAL FATIGUE SPECIMENS
WITH VARIOUS LEVELS OF
CONTROLLED POROSITY
(MAXIMUM STRESS = 55,000 PSI, S.R. = 0.1)

	Radiographic Porosity Level (ASME Boiler and Pressure Vessel Code Specification, Section VIII)					
Parameter	Base Material	Water Clear	Fine	Medium	Large	Assorted
Slope	3.38	1.79	1.39	1.04	.80	.74
Mean Life (Cycles)	448,984	222,891	160,698	181,000	239,879	292,715
Median Life (Cycles)	448,948	204,440	135,551	129,032	134,496	148,811
Characteristic Life (Cycles)	500,342	250,778	176,310	183,753	213,326	243,828
Std. Deviation	147,339	128,763	116,909	174,760	301,426	400,800

TABLE VIII

UNIAXIAL FATIGUE TESTS OF ARMOR STEEL (MIL-S-12560-B)* IN TENSION-TENSION AT A STRESS RATIO OF 0.1

Porosity Level	Maximum Stress, psi	Cycle Life
Clear	100,000	1,500
Large	100,000	150
Large	85,000	3,400
Base	75,000	1,940,000 (run out)
Base	80,000	207,900
Base	80,000	227,500
Medium	80,000	13,000
Fine	80,000	20,000
Base	80,000	292,000
Clear	80,000	132,000
Clear	80,000	870,000
Fine	80,000	149,000
Fine	80,000	34,000
Large	80,000	212,000

*Tempered to Rc 25

TABLE IX
V-NOTCH SQUARE CHARPY IMPACT
RESULTS (ROOM TEMPERATURE)
AND CALCULATED KIC VALUES
FOR VARIOUS POROSITY LEVELS
IN IH-50X WELD PLATES

Spec.#	Porosity Level	Impact Energy, Ft.-Lbs.	Calculated KIC, Ksi-in$^{\frac{1}{2}}$
7	Clear	95	152.1
3	Clear	83	141.4
8	Clear	99	155.3
13	Fine	93	150.4
15	Fine	100	156.1
17	Fine	110	164.0
4	Medium	85	143.6
5	Medium	88	146.2
11	Medium	89	147.0
16	Medium	102	157.7
1	Assorted	76	135.6
2	Assorted	77.5	136.9
6	Assorted	88.5	146.6
9	Large	32	85.9
10	Large	70	129.9
14	Large	98.5	154.9

TABLE X

UNIAXIAL FATIGUE RESULTS OF IH-50X WELD SPECIMENS WITH VARIOUS POROSITY LEVELS (ULTRASONIC) TESTED AT 55,000 PSI, MAXIMUM STRESS, S.R. = 0.1

Sample No.	Ultrasonic Category	Cycles to Failure
	CLEAR	
8	.6	161,800
34	.8	312,000
2	1	198,000
35	1	128,000
36	.8	421,000
	FINE	
33	2	312,300
6	3	42,900
18	3	153,400
17	2.5	30,700
3	2	198,000
37	2	413,300
7	2	282,100
11	2	45,000

TABLE X (Cont)

	MEDIUM	
27	4	86,300
21	5	71,500
24	6.5	43,300
39	7	67,200
	(omitted)	
26	7	543,000
	ASSORTED	
12	11.2	242,600
25	8	97,600
20	10	96,800
5	8	20,600
40	9	103,200
42	10	43,700
	LARGE	
13	11.4	201,400
15	14.5	365,900
10	13.5	575,700
4	14	17,300
22	16	220,100
16	13	25,200
14	16	309,000
38	15	42,000
41	13	93,400

TABLE XI

WEIBULL PARAMETERS FOR IH-50X
UNIAXIAL FATIGUE SPECIMENS
WITH VARIOUS LEVELS OF
CONTROLLED POROSITY
(MAXIMUM STRESS = 55,000 PSI, S.R. - 0.1)

Ultrasonic Grouped Porosity Level

Parameter	Base Material	Water Clear	Fine	Medium	Large	Assorted
Slope	3.38	2.06	1.01	0.87	0.86	1.20
Mean Life (Cycles)	448,984	249,210	208,412	188,491	235,158	109,483
Median Life (Cycles)	448,948	235,757	146,002	114,882	142,586	85,973
Characteristic Life (Cycles)	500,342	281,545	209,646	175,373	218,130	116,568
Std. Deviation	147,339	126,877	205,898	218,393	273,907	91,419

APPENDIX

This Appendix describes and discusses the ultrasonic test procedures for detection and measurement of various porosity levels in steel weldments. Ultrasonic porosity rating can be expressed in terms of a select porosity size (ultrasonic category or signature no.) or distribution of various size pores (ultrasonic porosity rating). Ultrasonic signature number is applicable to a certain pore size and requires the use of a digital display voltmeter connected to the conditioned ultrasonic output terminal.

In this study, an analog to digital converter, which is synchronized with the ultrasonic pulser, samples and selects the various pore sizes for assimilation into computer memory. A calculated porosity rating is then generated from stored data representing various pore sizes.

1. EQUIPMENT

1.1 Ultrasonic Instrument

The ultrasonic instrument shall be capable of performing the following requirements.

a. Generate and receive pulse of 2.25 and 5 MHz frequency energy.

b. Oscilloscope screen presentation and an analog output capability.

c. A receiver band pass of 1.3 MHz.

d. The pulse repetition rate shall be within 500 pps to 1000 pps.

e. The analog output voltage for full scale (2 inch amplitude on oscilloscope) should not vary more than 0.050 inch.

f. Coaxial cable length (terminal plug-in at pulser/receiver module) should be correct dimension to obtain optimum impedance matching with the search unit selected. A 30 ft. cable length provides adequate impedance matching with a 5 MHz search unit.

1.2 Search Units

For immersion type testing, spherically focused search units are recommended. Lithium sulfate type active elements provide for sensitive response and efficient converstion of reflected mechanical energy to electrical energy. The recommended frequency and focal length of the search unit in water is 5.0 $\pm$ .5 and 7.5 $\pm$ .3 inch, respectively.

For contact type testing, an angle beam (45^{o}) shear wave mode of inspection is recommended. Transducer type produced satisfactory inspection response with the 3/4 inch thick plates. Oil (S.A.E. 10W) or glycerine were found to be suitable couplants for transmission and receiption of ultrasound waves using contact search units.

1.3 Pulse Counter

A sixteen level pulse counter in the form of an analog to digital converter which is interfaced with a digital computer is recommended for rapid assimilation and data processing. An interface module is required to condition the ultrasonic analog signal for acceptance by the computer. A voltmeter is also required to monitor the conditioned voltage. Sixteen count levels are achieved by dividing the total voltage response range of the computer by sixteen. For a voltage range of 10 volts, each count level is a multiple of 0.625 volts (10 volts/16 levels). Ultrasonic determination of pore size by contact angle beam method can be monitored by noting the displayed voltage level or automatic printout of the ultrasonic signature (1 through 16) level corresponding to the voltage level.

2.0 CALIBRATION

Reference calibration blocks are required in which (1) flat bottom holes of 1/16", 1/8", 3/16" and 1/4" diameters have been drilled to a depth of one-half plate thickness and (2) actual defect standards representative of fine, medium, large and mixed porosity levels are available.

2.1 Ultrasonic Calibration and Control Settings

Prior to adjusting computer interface controls, adjust ultrasonic main frame controls as follows:

Pulse length	Minimum, full CCW
Reject	Off
Sensitivity	Maximum
Frequency	Frequency of search unit

To adjust ultrasonic sensitivity control for immersed longitudinal beam scanning, position search unit perpendicular to sound entry surface of reference block. Align search unit over (2 inch) flat bottom hole which is largest acceptable pore size viz. 3/16 inch diameter. Water path to sound entry surface is 2 inches. Ultrasonically locate (manual) 3/16 inch dia. hole. Reduce ultrasonic sensitivity control to obtain a 2 inch video amplitude response from 3/16 inch dia. reference hole.

To adjust ultrasonic sensitivity control or immersed angle (45^{o}) beam inspection, incline or angulate transducer 19^{o} from vertical and perpendicular position. With search unit angled at 19^{o}, lower search unit to obtain a height of 1.4 inches between search unit lens and sound entry surface. Adjust lateral displacement of search unit from reference hole to obtain a video display. Reduce sensitivity to obtain 1 inch video amplitude signal on CRT. Position search unit at edge of weld plate with shear wave beam pointed in direction of edge. Slowly move transducer away from edge until a signal

response (greater than 1 inch amplitude) appears on CRT. This signal reflected from bottom corner edge of the plate establishes search unit position for half-skip target defect position which is equal to the plate thickness. Note position of defect signal on CRT. Continue moving transducer away from edge until a signal reappears on CRT. This signal reflected from the top corner edge establishes search unit location for a full skip distance to defect position or twice plate thickness (1½ inch). Record position of search unit from plate edge and record position of signal trace on CRT. Reposition search unit to obtain 1 inch signal response (on CRT) from 3/16 inch diameter hole. The horizontal distance between search unit and reference hole (Figure 38) should be equivalent with previous horizontal distances to bottom corner edge. Adjust ultrasonic sensitivity control to obtain a 2 inch video signal.

To assure complete ultrasonic coverage of the weld area during inspection, the search unit position and bridge scanner are initially set at the limit position for a full skip. A parallel scan (8 in/sec) of the weld seam is conducted with data printout at end of scan. The positioner is laterally indexed (0.050 inch) in direction of full skip limit position and a data printout is automatically furnished. This inspection process is repeated until the full skip limit position is reached. Figure 40 shows the scanning pattern and limit positions with reference to the weld seam.

Calibration for contact angle beam inspection is the same as immersed angle beam inspection. However, due to manual movement of the search unit, a different scanning pattern is used. Additionally, the output of digital voltmeter or corresponding ultrasonic category level is printed out in lieu of porosity distribution rating.

Figure 41 shows the saw tooth scan pattern for contact inspection between limit positions with reference to the weld seam. With manual scanning, the search unit can be rotated about its vertical axis upon encountering a large pore site to determine maximum response from variable search unit orientation. Rotation is approximately $\pm$ 30° from search unit normality with weld seam.

2.2 Computer Interface Control Settings

The primary function of the computer interface is to (1) condition the ultrasonic output voltage for compatability with input computer requirement (2) use a synchronization signal for timing analog to digital conversion and (3) provide amplification means for adjusting the low and high ends of the conditioned signal. This control assures that correct voltage is linear and matched to the ultrasonic count level. Adjust the interface offset control to read 9.7 volts (mid range of count level 16) on the digital voltmeter with a 2 inch video amplitude signal displayed on the ultrasonic scope. Next adjust ultrasonic sensitivity control to obtain a .2 inch amplitude signal. Adjust interface fine sensitivity control to obtain a reading of 0.97 volts on the digital voltmeter. Reset the ultrasonic sensitivity control to obtain a 2 inch video amlplitude.

Reference standards which contain the various porosity grades such as fine, medium and large should be ultrasonically examined using longitudinal and shear wave modes. Corresponding ultrasonic category and voltage response should be noted and recorded for each standard. With shear wave inspection, the ultrasonic beam direction should be varied for several search unit orientations.

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Army Materials and Mechanics Research Center
Watertown, Massachusetts 02172
ULTRASONIC INSPECTION AND FATIGUE
EVALUATION OF CRITICAL PORE SIZE
IN WELDS
Clarence J. Carter, John J. Connelly
and Raymond A. Cellitti
International Harvester Company
Science & Technology Laboratory
Hinsdale, Illinois 60521

Technical Report AMMRC TR 80-35, Sept. 1981, 76 pp-
illus, D/A Project M766350 PEMA
AMCMS CODE 5397-OM-6350

UNCLASSIFIED

Key Words

Weld
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Porosity
Ultrasonic Tests
Fatigue

Controlled amounts of weld porosity were introduced into double-vee butt weld joints of low-alloy, high strength structural steel using a gas metal arc weld method. The weld zones were inspected radiographically and ultrasonically to detect and classify porosity severity. Subsequent uniaxial fatigue tests indicated that mean fatigue life was not significantly (7%) influenced by pore severity between "water clear" weld and weldments with large pores (3/16 inch diameter). Fracture toughness (KIC) as measured by Charpy impact under dynamic loading was noted to improve with weld specimens containing fine pores (0.024 inch diameter and under).

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